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# NDI ORIENTED CORROSION CONTROL FOR ARMY AIRCRAFT: PHASE I – INSPECTION METHODS

Final Report

SwRI Project 17-7958-843

Prepared for

U.S. Army Aviation Systems Command
Depot Engineering and RCM Support Office
Corpus Christi Army Depot
Corpus Christi, Texas 78419-6195

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**SOUTHWEST RESEARCH INSTITUTE**
SAN ANTONIO                              HOUSTON

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Performed as a Special Task under the auspices of the
Nondestructive Testing Information Analysis Center
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The purpose of the work in this project was to assess the extent of corrosion in Army aircraft and its cost, to investigate nondestructive inspection (NDI) methods of corrosion control, and to formulate specific recommendations for detecting corrosion in new and fielded Army aircraft. The work focused on corrosion detection based on techniques in place and on the latest NDI techniques taking into account the type and stage of corrosion. Included was investigation of the application of NDI methods at critical points in the Corpus Christi Army Depot (CCAD) operation in order to better detect, prevent, and control corrosion in aircraft components as a result of depot maintenance. A key task involved determining how to proceed in developing an NDI oriented manufacturing model for CCAD into which can be incorporated candidate NDI methods that would improve the prevention of corrosion during CCAD's depot maintenance/NDI operations. Effort was concentrated on structuring a flexible manufacturing system (FMS) model for CCAD, including the defining of an FMS cell for support of corrosion control. The report contains a summary of the NTIAC State-of-the-Art (SOAR) on "Nondestructive Evaluation methods for Characterization of Corrosion."

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# TABLE OF CONTENTS

# 1.0 INTRODUCTION

# 1.0 INTRODUCTION

This document forms the final report for the NTIAC Special Task 17-7958-843 "NDI Oriented Corrosion Control for Army Aircraft: Phase I Inspection Methods." All of the information contained herein has been furnished to the U.S. Army Aviation Systems Command (AVSCOM) Depot Engineering and RCM Support Office (DERSO) during the project as specific reports, camera-ready copy for materials to be published at AVSCOM, visual aids packages, or other documents. Those materials are brought together here to have a complete record of what was accomplished and what has been furnished to DERSO.

The purpose of the work in this project was to assess the extent of corrosion in Army aircraft and its cost, to investigate nondestructive inspection (NDI) methods of corrosion control, and to formulate specific recommendations for detecting corrosion in new and fielded Army aircraft. The major portion of the work was accomplished by Reliability Technology Associates (RTA) as a subcontractor to Southwest Research Institute (SwRI) and the Nondestructive Testing Information Analysis Center (NTIAC) which was responsible for reviewing RTA reports and furnishing information on NDI of Corrosion.

The work focused on corrosion detection based on techniques in place and on the latest NDI techniques taking into account the type and stage of corrosion. Included was investigation of the application of NDI methods at critical points in the Corpus Christi Army Depot (CCAD) operation in order to better detect, prevent, and control corrosion in aircraft components as a result of depot maintenance. A key task involved determining how to proceed in developing an NDI oriented manufacturing model for CCAD into which can be incorporated condidate NDI methods that would improve the prevention of corrosion during CCAD's depot maintenance/NDI operations. Effort was concentrated on structuring a flexible manufacturing system (FMS) model for CCAD, including the defining of an FMS cell for support of corrosion control.

As the only coherent assembly of the results of this project for DERSO, the report contains a summary of the NTIAC State-of-the-Art Review (SOAR) on "Nondestructive Evaluation Methods for Characterization of Corrosion." The summary extracts information on corrosion specifically related to Army aircraft corrosion. There are 40 references retained in the summary as compared to 131 references in the original SOAR. A complete copy of the SOAR was provided to DERSO when it was published.

The second item provided by NTIAC is a bibliography of NDE for FMS. The bibliography, with abstracts, was obtained from the data bases of NTIAC and MTIAC (Manufacturing Technology Information Analysis Center) and is to support the information on FMS supplied by RTA.

A listing of meetings and site visits by RTA and SwRI is provided.

The remaining materials incorporated into this report are the materials developed by RTA and furnished directly to DERSO. These materials are listed in chronological order except for the visual aids and the Pamphlet Series 750-2 materials and associated Aircraft Analytical Corrosion Evaluation (AACE) worksheets which are in Appendices A and B and are provided as cover sheets from each item rather than complete packages. The Pamplet Series materials were furnished as camera-ready copy and were published by AVSCOM. Army aircraft covered in the series include models: UH-1 H/V, OH-58, AH-1/TH-1, CH-47, UH-60, and AH-64.

Complete reports incorporated into this report begin with: (4.0) "Improved Storage Methods of Parts at CCAD Work Centers" sent to DERSO December 10,1987, through (13.0) "Machine Support Element Issues

in FMS Cell Definition" sent to DERSO June, 1989. Draft and preliminary reports submitted for review and/or revision have not been included.

This report, along with the separately submitted reports, visual aids, Pamphlets, and work sheets, constitutes completion of the work under the subject program including the three contract modifications which added establishing profile index data and AACE thresholds for aircraft in the program, perform a cost/benefit analysis for CCAD manufacturing model, and evaluation/preparation of an FMS cell documentation.

## 2.0 NONDESTRUCTIVE EVALUATION METHODS FOR CHARACTERIZATION OF CORROSION IN HELICOPTER COMPONENTS

# 2.0 NONDESTRUCTIVE EVALUATION METHODS FOR CHARACTERIZATION OF CORROSION IN HELICOPTER COMPONENTS

This chapter summarizes the NDE methods presently being used for detection and evaluation of helicopter and aircraft corrosion. These include visual, magnetic, thermographic, electrochemical, acoustic emission, eddy current, liquid penetrant, and x-ray and neutron radiographic methods. Their advantages and limitations are part of the discussions. The summary also addresses corrosion problems of the United States Army, Air Force, and Navy aircraft and helicopter fleets. The coverage of military helicopter/aircraft corrosion problems is by no means inclusive in this summary. Included with these problems are presently applied NDE methods, where appropriate, and identification of the new methods if conventional methods are not applicable.

The material in this chapter was condensed from a recent comprehensive state-of-the-art review (1) ("Nondestructive Evaluation Methods for Characterization of Corrosion") to focus on the information relevant to helicopter corrosion problems and needs.

## I. INTRODUCTION

Corrosion is a major maintenance problem that has been rapidly expanding with the growth in aging helicopter components. The question now is whether to replace a component or to inspect and repair. Replacement can be performed on low-cost items, but inspection and repair have been the preferred route for the high-cost items. While the inspection and repair approach is justified, the reliability of certain nondestructive evaluation (NDE) inspections is questionable. Methods for detection of hidden corrosion, measurement of material degradation due to corrosion, and quantification of corrosion are not fully developed. The need for improving inspection methods is, however, accelerating with the increasing inventory and age of defense equipment and with the high cost of adding new equipment.

Corrosion has been defined as the degradation of a material or its properties because of a reaction with its environment (2). Within the scope of this definition, degradation by corrosion, or corrosion damage, can take many forms. The most common are localized damage such as pitting of a surface, generalized attack where a more or less uniform loss of material occurs over a large surface area, environmental cracking in which the combined effects of corrosion and stress can lead to early failure, and some forms of property degradation such as the preferential loss of an alloying agent. The mechanisms by which corrosion damage occurs are also varied, but can be classified generally as electrochemical, chemical, or physical.

Recognition of the severity of the problem by various industries and governmental agencies has led to a significant effort within the past 50 years to prevent and control corrosion. Nondestructive evaluation (NDE) plays an important role in this effort, mostly by providing detection of the early signs of corrosion so that corrective action can be taken before damage becomes severe. As the cost of repair or replacement continues to increase, demands on NDE, particularly for early detection corrosion, also will increase. The purpose of this summary is to identify the NDE technology currently available or emerging that is or could be applicable to detection and evaluation of corrosion in helicopter components and structures.

Section II of this chapter is a description of the nature of corrosion damage and a summary of its physical factors for use in corrosion detection. The next section is a review of corrosion NDE methods, including those in use and under development. Section IV addresses corrosion detection needs of the U.S. Army, Air Force, and Navy. The final section contains the references, and a glossary of corrosion-related terms is presented in Appendix A.

## II. CHARACTERISTICS OF CORROSION

### A. Corrosion Damage

#### 1. Overview

The simplest form of corrosion damage (3) is general attack when a more or less uniform loss of material occurs over a surface. In most cases, general attack is caused by very small anodic and cathodic areas on the surface, which switch places as the process continues. The end result is that at one time or another all regions of the surface are anodic, and material loss over a sufficient length of time is approximately uniform.

In discussing the NDE of corrosion, it is convenient to divide the remaining forms of corrosion damage into three classes depending on the type of damage observed. The first is localized corrosion, which results in the formation of pits or similar defects. The second is environmental corrosion, which includes the corrosion-enhanced formation of cracks; and the third is degradation of properties in the absence of crack or pit formation.

#### 2. Localized Corrosion

Many forms of localized damage are the result of localized corrosion cells with anode and cathode in close proximity on a surface. Pitting is a particular form resulting from metal loss at a local anode and leading to cavity formation. Shapes of pits vary widely; some are filled with corrosion products while others are not. This form of damage is often observed in metals that are coated or otherwise protected by a surface film, and is probably associated with damaged or weak spots in the coating.

Crevice corrosion is a special form of pitting occurring at crevices or cracks formed between adjacent surfaces. The corrosion mechanism in this case is usually the formation of an oxygen concentration cell, with metal loss in the crack or crevice with a low concentration of oxygen.

Poultice corrosion is similar to crevice corrosion in that an oxygen concentration cell is involved. With poultice corrosion, however, the anodic region of low oxygen concentration is covered by some foreign material on the surface, and metal loss occurs under the covering.

Filiform corrosion is still another form involving oxygen concentration cells, in this case under organic or metallic coatings. Damage is characterized by a network of threads or filaments of corroded material under the surface.

Galvanic attack can also cause pitting of the more active of two dissimilar metals in contact. Depending on the relative areas of the anodic and cathodic surfaces, this form of corrosion can lead to a more dispersed metal loss. Thus, if the anode area is large compared to the cathode area, damage to the anode will tend to be more uniform than if the reverse were true.

In all of the cases just described, the mechanism leading to localized damage is electro-chemical in nature. Certain physical forms of corrosion, however, can also produce localized damage. One of these is fretting, in which metal is removed by the abrasive action of one surface moving against another.

#### 3. Property Degradation

In addition to producing defects such as pits or cracks, corrosion can also lead to the deterioration of material properties without the presence of flaws that might be detectable with

conventional NDE. Examples of property degradation are intergranular and transgranular corrosion, corrosion fatigue, and dealloying.

Intergranular corrosion is a highly localized form of damage in which attack occurs along a narrow path that tends to follow grain boundaries. Its cause is from a potential difference developing between the grain boundary and surrounding material, which, in turn, is caused by the trapping and precipitation of impurities at grain boundaries. Because of this dependence on grain-boundary composition, susceptibility to intergranular attack is strongly dependent on metallurgical treatment. In particular, the heat-affected zone near a weld is a region where the temperature produced during the welding process causes impurities to migrate and become trapped at grain boundaries. The heat-affected zone can, therefore, be susceptible to intergranular corrosion.

Transgranular corrosion is similar to intergranular corrosion in that attack is highly localized and follows a narrow path through the material. As the name implies, the paths in this case cut across grains with no apparent dependence on grain-boundary direction. Transgranular corrosion is often associated with corrosion fatigue although intergranular and sometimes both intergranular and transgranular corrosion are observed.

Corrosion fatigue is a term applied to the degradation of fatigue life in a corrosive environment. It is distinguished from environmental cracking in the sense that corrosion fatigue refers to degradation by any corrosive environment and is not specific to a particular mechanism, while environmental cracking relates to specific forms of damage. Corrosion fatigue is distinguished from environmental cracking by the morphology of the fractured surface.

## B. Corrosion Detection and Measurement

The objectives of corrosion NDE are to detect and measure the extent of corrosion damage and/or corrosion activity. As usually in NDE, emphasis in damage detection is on small flaws, so that repair or replacement of parts and possibly correction of the corrosive environments can be accomplished at minimum cost.

Corrosion NDE is different from other applications because an estimate of corrosion rate may be needed in addition to a measurement of existing damage. To make a cost-effective assessment of the need for corrective action, sometimes identifying flaws of a given type and size in a particular location is not enough. Information on corrosion activity is also needed; i.e., the rate at which damage is occurring. Periodic repetition of an inspection is one means of monitoring flaw growth rate. This approach does, however, require accurate measurement of flaw size. Other alternative measurement approaches more directly related to corrosion rate also are available. But regardless, the need for rate information places additional demands on corrosion NDE over flaw detection alone.

Additional differences exist between corrosion NDE and other applications. Corrosion products, for example, provide an opportunity for NDE that does not exist in a noncorrosive environment. This part provides a brief review of the physical manifestations of corrosion useful when assessing the need for NDE.

The detection of corrosion pits, cracks, or wall thinning due to general attack of a surface are examples of corrosion NDE problems that differ only in detail from problems encountered in other branches of NDE. For this reason, most of the corrosion NDE examples cited in the next section are simply adaptations of conventional NDE methods to corrosion problems--with a few differences. For example, if a corrosion pit is partially filled with a corrosion product with nearly the same physical properties as the host material, then detection and sizing of the flaw are more difficult than would be the case in the absence of corrosion products. The detection of crevice or poultice

corrosion might also be more difficult than detection of other types of flaws because the damage is hidden in a crack or crevice or under a patch of material on the surface of the part.

In principle, electrochemical corrosion always generates corrosion products, although these products are not always detectable. One detectable corrosion product, often by a simple visual inspection, is oxide produced in the corrosion of aluminum. Other products, plus the physical or chemical effects associated with corrosion products, form the basis for corrosion detection.

## III. NONDESTRUCTIVE TEST METHODS FOR CORROSION ASSESSMENT DETECTION

Inspection for corrosion to date has generally been performed by either directly applying the conventional NDE methods or applying after slight modifications. In general, NDE for corrosion has been directed toward finding the appropriate conventional method that can perform such an inspection. This fact was also supported by a survey on corrosion monitoring methods performed in the U.K. (4). Thus, very few specific NDE methods exist for corrosion. This section includes a spectrum of the methods applied for a range of corrosion problems. Included are both the application of conventional methods and discussion of novel methods for corrosion NDE.

### A. Acoustic Emissions

Acoustic emission (AE) refers to the generation of elastic waves in a material caused by its deformation under stress. Flaws can be detected using AE methods because flaw growth caused by stresses produces acoustic emissions. Material stress can come from mechanical and thermal loading, as well as from a variety of other means.

AE from materials is generally one of two types. The first is low-level and almost continuous. This AE, similar to background noise, can be from plastic deformations, microstructural changes, or a chemical reaction related to corrosion. Low-level AE can also be produced by flaking or removal of corrosion products from a surface. High-level signals in the form of bursts are generally associated with sudden release of energy such as growth of discrete flaws like cracks, the burst of bubbles, and cavitation.

The most common tests for AE are on-line monitoring and proof. On-line monitoring is a passive method where AE is recorded for a long time. Flaws are detected by changes in the AE from the background noise level. The proof test is different from on-line monitoring, as it employs application of an additional load to produce AE. This external load forces the flaws to grow and produce AE. The proof test is short term compared to on-line monitoring.

Cracking of the corrosion-product film will produce detectable emission. The energy source is the elastic stress field that develops during film growth or temperature change and releases during sudden cracking, spalling, or exfoliation. Thick, brittle, tenacious films, in general, produce higher amplitude emissions than thin, soft, or weak films; emission may not be detectable for the latter type.

#### 1. Detection of Surface Corrosion

Detection of surface corrosion by AE has been performed for a variety of applications. These methods detect corrosion by detecting AE generated from the breaking of corrosive films or products, chemical reaction, or bursting of bubbles.

Detection of corrosion in aircraft honeycomb structures has been performed at McClellan Air Force Base (5). The test was conducted by heating a local area of the structure and monitoring

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the AE produced by evolution of hydrogen gas or steam. AE from the corroded areas was only detectable for wet areas and not from dry ones.

Birring (6) has performed an AE test on corroded parts obtained from an aircraft. AE activity monitored during application of heat showed that corroded parts produced 15 times the amount of AE counts compared to the noncorroded parts (see Figure 1). The AE method was unsuccessful on parts with no deposits of corrosion products. The test concluded that the AE was produced by the breakage of the corrosion film and that AE testing would detect the breakage of corrosion film during thermal expansion.

## 2   Cracking

Feist (7) has applied AE to find detection of intergranular cracking in gas-turbine blades. Such cracks can be significant when present in the area of the fir-tree grooves and the blade root. AE was produced from the microcracks by applying thermal-shock loading. The root area of the blade was heated with an induction coil and quenched. Acoustic emission signals then received were used to detect cracking with a depth range of 10 to 100 microns. This same approach is potentially useful for other components such as highly stressed forgings.
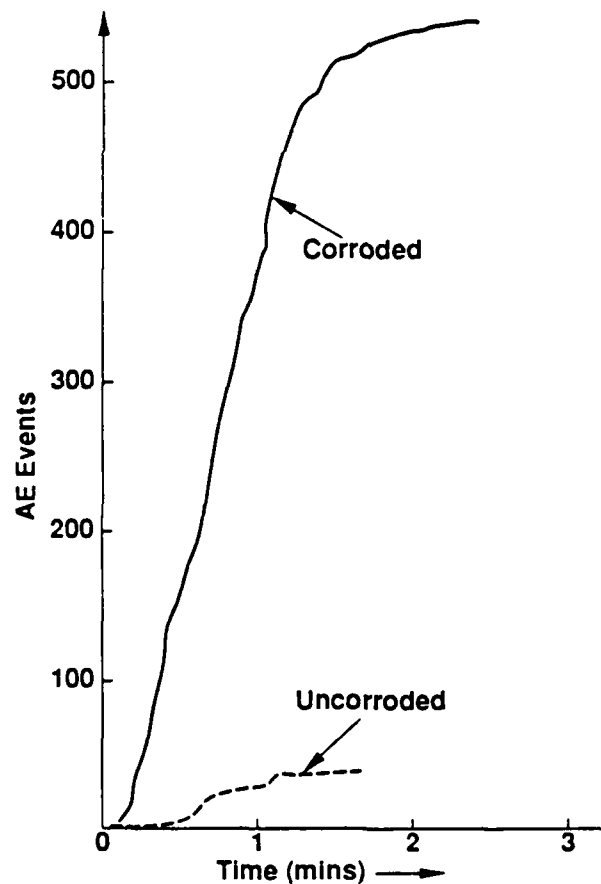


Figure 1.   Acoustic emission counts recorded while heating corroded and uncorroded specimens. The acoustic emission counts on the corroded specimen were more than 14 times greater than those on the uncorroded specimens (6).

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## B. Eddy Current

Eddy current testing (ET) techniques are useful in the detection and sizing of many types of defects related to corrosion damage. In addition to its well-known applications to crack and pit detection, eddy current can be used to measure thickness changes caused by corrosion, buildup of corrosion products in certain situations, and some changes in material properties such as conductivity degradation caused by intergranular corrosion. The techniques and applications reviewed here include examples of each of these uses of ET.

Corrosion NDE involves a variety of ET techniques ranging from simple applications of well-established inspection procedures to advanced techniques based on the latest developments in eddy current research. While some of the examples cited here focus on the measurement of only one flaw characteristic such as the depth of a corrosion pit, others demonstrate the ability of a particular technique to detect and characterize more than one aspect of corrosion damage. Some of these multipurpose techniques are discussed first, followed by reviews of techniques for crack and pit detection, measurements of material thickness, and detection of material-property changes.

### 1. General Applications of Eddy Current Techniques

If the thickness of a part is on the order of or less than the skin depth, the phase lag of the eddy current probe impedance, relative to the phase of excitation current, can be related to thickness. This well-known technique was used, for example, by Bond (8,9) for the detection of panel thinning and corrosion pit detection in the inspection of aircraft structures. Instrumentation requirements, sensitivity, and the practical aspects of routine inspection for corrosion were also discussed by Bond.

Hagemaier (10-12) used both amplitude and phase information to make quantitative measurements of panel thickness. He inserted an aluminum taper gauge under a probe to provide an impedance plane trajectory as a function of aluminum thickness. Calibration data were obtained from panels of known thickness, and these data formed the basis for thickness determinations with panels of unknown thickness. Even though the calibration data were based on specimens of uniform thickness, the taper-gauge approach has been applied in the characterization of localized thinning caused by corrosion pits. The detection of cracks and foreign material in multilayered structures were also discussed in Hagemaier's publications.

A different application of the phase/thickness relationship was discussed by Rowland et al. (13). They describe the remote-field eddy current effect for the inspection of multilayer, parallel-plate structures. The remote-field technique is normally used for inspection of cylindrical pipes from the inside (14-16). The effect, explained in detail in the referenced articles, is the observed linear variation of phase with pipe-wall thickness when transmitter and receiver coils are separated by about two pipe diameters. Rowland et al. have demonstrated that the same effect is observed in parallel plate structures and can be used to measure plate thickness. They also discussed the uses of unusual eddy current probe configurations for locating corrosion damage and inspecting fastener holes.

### 2. Crack Detection

While the principle of eddy current crack detection is the same, the nature of corrosion-related cracks can be quite different from, say, isolated fatigue cracks. Intergranular stress-corrosion cracking (IGSCC), for example, is often characterized by a multitude of multiply branched cracks in the region where damage has occurred. The interaction of an eddy current field with such a region is more complex than the interaction with a single crack of simple geometry. An eddy current scan over a region with IGSCC can produce an impedance plane trajectory that more closely resembles the signal from a region of low conductivity than the signal from a crack.

Almost all discussion of crack detection in the literature is concerned either with simply shaped, isolated cracks (whether corrosion related or not) or with property changes associated with stress-corrosion cracking. One exception is the work of MacLeod and Brown (17), which was specifically directed at the detection of stress-corrosion cracks in aluminum forgings. Most of their discussion concerned the development of an automated, motor-driven system for wheel hub inspection. Applications to other aspects of aircraft inspection and maintenance were also reviewed.

### 3. Pit Detection

Both amplitude and phase measurement techniques are used in corrosion pit detection and sizing. With the amplitude method, one assumes that the amplitude of an eddy-current signal is proportional to the depth of a pit. The phase-sensitive technique assumes that remaining wall thickness can be related to the phase of the signal from a pit.

### 4. Material Loss

In corrosion monitoring applications, measurement of wall thinning due to loss of material is probably the most common use of eddy-current testing. The linear relationship between phase and wall thickness forms the basis for such measurements.

If the structure to be inspected consists of more than one layer, interpretation of phase-shift data becomes more complicated. In the problem addressed by Hayford and Brown (18), the material of concern was an aircraft structural member to be inspected through an outer layer of aircraft skin. When corrosion occurs on the outside surface of the inner material, corrosion product buildup can cause an increase in the separation of the layers, accompanied by a decrease in the thickness of the inner (second) layer, its thickness decreases; but there is no change in the air gap between the layers. To further complicate matters, the air gap itself may vary from place to place in the absence of corrosion.

### 5. Material Properties

During the early stages of corrosion damage, changes in near-surface properties can occur as a result of intergranular corrosion, formation of corrosion products, or other oxidation and reduction processes. In certain instances, these material-property changes can be observed in an eddy-current test through an accompanying change in the conductivity or permeability in the surface layer exposed to the environment.

Most studies of corrosion-related property changes are concerned with electrical conductivity degradation due to intergranular attack (IGA) or SCC. As noted earlier, sometimes IGA and SCC cannot be distinguished by the eddy-current technique because signals from individual cracks cannot be resolved and both IGA and SCC are observed as a decrease in the effective conductivity of the damaged region. This has led several workers to study localized conductivity variations and their measurement by the eddy-current technique as a means of detecting and measuring IGA or SCC.

In one such investigation, Naumov et al. (19) attempted to correlate the absolute conductivity of an aluminum alloy with the depth of intercrystalline corrosion. They were unable to establish such a correlation because the absolute conductivity seemed to depend on other factors related to variability of the material before corrosion was initiated. On the other hand, they did find a good correlation between depth of corrosion and the change in conductivity caused by corrosion.

### 6. *Other Corrosion-Related NDE Considerations*

In addition to causing damage to a material, corrosion can inhibit the detection of defects caused by other factors such as fatigue. De Graf and De Rijk (20) studied the deleterious effect of corrosion on the probability of detection (POD) of fatigue cracks in aluminum panels using ultrasonic, liquid penetrant, and eddy-current methods. Before corrosion of the panels, the POD was best for penetrant inspection, with eddy current being the second most effective. After corrosion, however, penetrant inspection results were poorer than eddy current, probably because corrosion products inhibited penetration of the liquid. In all cases, the POD was significantly reduced by corrosion, but eddy current detection suffered less than detection by the other methods.

### C. Liquid Penetrant

Liquid penetrant testing (PT) method is commonly used for surface inspection to detect cracks or other discontinuities. The penetrant can be either a colored dye or fluorescent that penetrates the defects by capillary action. After a short time, excess penetrant is wiped off the surface and a developer applied. The developer draws the penetrant out of the cracks and spreads it on the surface indicating a flaw. A crack is indicated by a continuous line, while pits are represented by dots.

Liquid penetrant has generally been applied for the detection of surface-opening cracks. The Turkish Air Force (21) inspects the rims of aircraft for cracks (including SCC) using PT. Another example for detecting SCC in the H-link connected to the landing-gear strut is the application of a fluorescent penetrant.

### D. Radiography and Radiation Gauging

In principle, radiographic NDE methods are capable of detecting and measuring both generalized and localized corrosion damage. With either type, corrosion is measured by analyzing the radiographic image through comparisons with calibration images of specimens of known thickness. If damage is localized, then calibration is not necessary for flaw detection alone because the presence of pitted areas is evidenced as regions where the image intensity differs from that of surrounding regions. If, on the other hand, damage occurs as uniform thinning, then comparison with a calibration image is necessary to determine the extent, if any, of material loss.

In x-ray transmission radiography, image contrast is determined by the attenuation characteristics of the specimen material and variations in the thickness of the irradiated part. Because x-ray attenuation is large in materials with high atomic numbers such as most engineering metals and alloys, loss of material results in a relatively large increase in the transmitted x-ray flux. The presence of a large corrosion pit is therefore evidenced by a localized region of higher x-ray intensity, which causes the gray-scale level of the image in that region to differ from that of neighboring regions.

Image formation with neutron radiography is somewhat different. Neutron attenuation is determined by the scattering and absorption cross sections of the elemental constituents of the material, and these cross sections vary greatly from one element to another. Of particular importance in corrosion NDE is the fact that hydrogen has a relatively large neutron cross section. Thus, because corrosion products are usually hydroxides, corrosion products often attenuate neutrons more than the base material. The neutron radiographic image is determined by the distribution of corrosion products rather than metal loss, as is the case in an x-ray radiograph.

This fundamental difference between neutron and x-ray radiography is well illustrated by the work of Rowe et al. (22), who used both methods in the inspection of aluminum-alloy airframe structures for corrosion damage. The neutron experiments were conducted with thermal (slow)

neutrons from a nuclear reactor, while x-ray radiography tests made use of conventional x-ray equipment. Realtime imaging systems were employed in both types of tests, and digitized images were subjected to various forms of digital image enhancement (22,23) to improve flaw detectability. Under laboratory conditions, the x-ray method was found capable of detecting metal thickness changes as small as 0.08 mm, and neutron radiography could detect hydroxide layers of the same thickness. However, because the corrosion product thickness in the system studied by Rowe et al. was estimated to be about three times the corresponding metal loss, the neutron method is about three times more sensitive in terms of metal loss.

The most serious obstacle, however, to implementation of neutron radiography in airframe inspection is that a portable neutron source of the intensity needed for this application is not presently available. While development of a suitable neutron source is feasible, Rowe et al. concluded that x-ray radiography, which has adequate sensitivity to corrosion damage, is presently the more cost effective of the two radiographic methods for airframe inspection.

The ability of neutron radiography to image corrosion products, particularly in aluminum structures, has motivated several researchers to explore applications to aircraft corrosion, with the work of Rowe et al. (22) being the latest example. Currently the USAF is installing three neutron radiographic facilities at the McClellan AFB in Sacramento, California (24). As was noted earlier, the principal difficulty with neutron radiography is the need for a large thermal neutron flux to form an image in a reasonable exposure time. A high-source strength, in turn, requires shielding to protect personnel from the radiation hazard. If a radioactive source such as Cf-252 is used, shielding must be provided at all times, except perhaps during the actual exposure when personnel can be excluded from the exposure site.

An alternative approach is to use a portable neutron generator, which is a particle accelerator producing neutrons through the deuterium-tritium reaction. The advantage offered by a neutron generator over a radioactive source is that the generator can be turned off, so no shielding is needed during transport and setup; the disadvantage is that neutron yield from commercially available devices is about an order of magnitude lower than desirable for radiography of large structures. Regardless, whether one uses Cf-252 or a neutron generator, the source must be surrounded by a moderating material to slow down the fast neutrons produced by the source to the thermal energies required for imaging.

The development of neutron generator systems designed specifically for radiography are reported by Dance et al. (25) and Kedem et al. (26). Both systems have the capability of source and imager positioning for radiography of sections of aircraft structures. From the brief description given in Ref. (26), this system seems to make use of near realtime video imaging with postprocessing capabilities for image enhancement. The mobile neutron generator/imager designed by Dance et al. was tested with several combinations of converter screens and films, as well as a low-light television imaging system. Reference (25) contains numerous examples of radiographs of aircraft structures obtained in field testing of the equipment. The system was delivered to the Army and is now installed at the Army Materials Technology Laboratory.

Another form of backscatter inspection was reported by Frasca et al. (27). They used backscattered beta radiation for the detection of corrosion products under an epoxy coating on an aluminum substrate. The system makes use of an $Sr^{90}$ - $Y^{90}$ collimated and shielded source with plastic scintillator detectors mounted alongside. Experiments with artificial flaws filled with corrosion products indicated that pit depths of 2 to 20 mils were detectable. Corrosion also could be detected on the backside of an aluminum or magnesium skin with thickness up to 20 mils.

## E. Thermography

Thermography is the study of the temperature pattern of a specimen's surface on application of heat. Thermography can be used to detect flaws because, after inducing a thermal impulse, the flaw affects the transient response of the surface temperature. This technique can also be used to detect loss of thickness by corrosion under paint.

McKnight and Martin (28) found infrared thermography to be a feasible method to evaluate the performance of coatings on steel in the laboratory. Although this work was done on steel, it is equally applicable to aluminum aircraft structure. The presence of localized corrosion products under an intact film and air- and water-filled blisters was observed as varying gray levels representing temperature variations. The localized corroded area appeared hotter than the surrounding area. Neither corrosion nor blistering was observed on visual inspection. They were able to resolve slightly corroded and blistered areas 1 mm in diameter on smooth substrates. For 50-$\mu$m profile sandblasted panels, the resolution was about 1.2 to 1.5 mm. For the coated panels exposed to an elevated humidity and temperature environment, water-filled blisters under a pigmented film and localized corrosion under a clear film could be detected if the diameter of the area were greater than 1 mm. They recommend further research to improve the resolution sufficiently to detect the initial breakdown of the coating/substrate interface on smooth or sandblasted substrates.

Birring et al. (6) also used thermography to successfully detect corrosion under paint. For the experiments, a 1500W lamp was used to heat the plate surface for a short time ($\approx$1 second). The surface temperature of the specimen was monitored by a thermovision camera. Photographs clearly showed the hot areas where corrosion was present. Besides the fact that the method successfully located corrosion on several plates, an additional advantage of thermography was its speed, which reduces inspection costs. This method also is easy to apply for aircraft inspections.

## F. Ultrasonics

Ultrasonics has been used to detect corrosion in a range of applications. In most of the cases, the conventional techniques have been directly applied or applied with minimal modification. These techniques are based on the analysis of high-frequency sound waves reflected/scattered from a discontinuity. The discontinuity could be a crack, pit, or any other anomaly that can be caused by corrosion. The most common analysis of ultrasound includes determining the reflected signal and measuring its amplitude and arrival time. A signal indicates a flaw or discontinuity with signal amplitude relating to flaw size and arrival time establishing flaw location. Advanced ultrasonic techniques include measurement of small changes in velocity (less than 1 percent), analysis of the backscatter from the microstructure, and application of complex wave modes. Enhancement of ultrasonic results is provided by imaging, signal processing, and pattern recognition. Some of the latest advances and future areas include application of electromagnetic acoustic transducers (EMATs) and phased-array technology.

### 1. Surface Corrosion

Surface corrosion is measured by the ultrasonic pulse-echo method, i.e., an ultrasonic transducer transmits waves towards the specimen; signals are reflected from the front and back surfaces, and the time difference between these two signals is used to measure the remaining thickness (see Figure 2). These measurements can be taken with commercially available digital thickness gauges if the specimens have smooth surfaces. The performance of the digital gauges degrades rapidly with an increase in surface roughness (29) (see Figure 3) because of ultrasonic scattering (see Figure 4). With extremely rough surfaces, performance degradation can cause random numbers to be generated by the digital readout. Digital thickness measuring instruments, therefore, are not recommended on rough surfaces. Instead, an analog representation of the signal
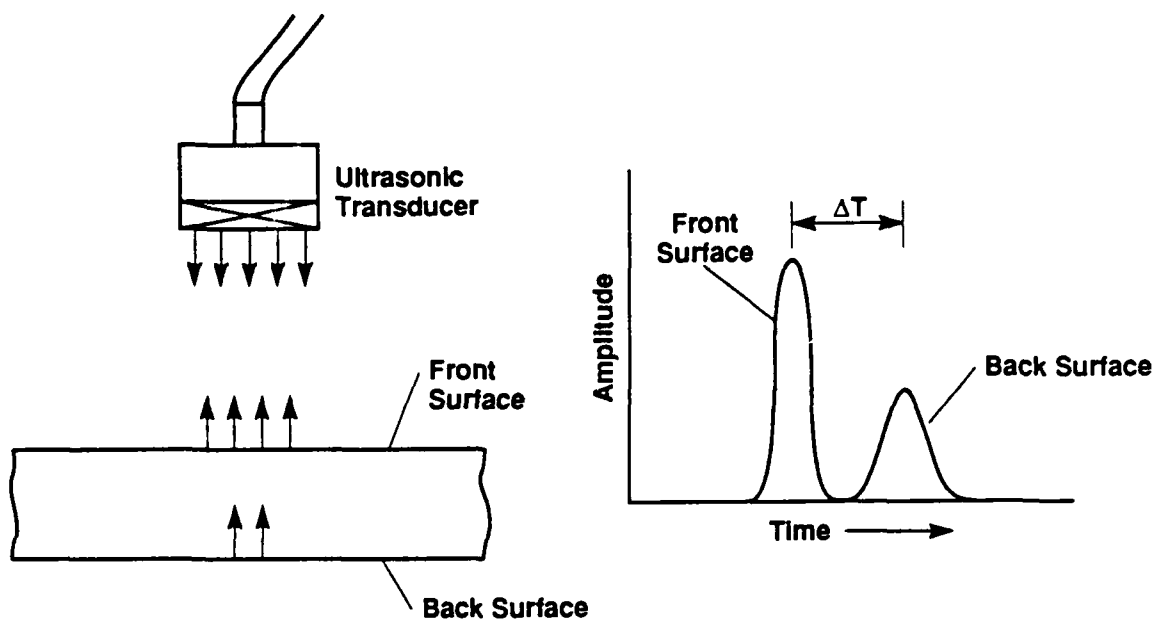
Figure 2. Thickness measurement method. The time difference between the ultrasonic signals reflected from the front and back surfaces is used to calculate thickness.
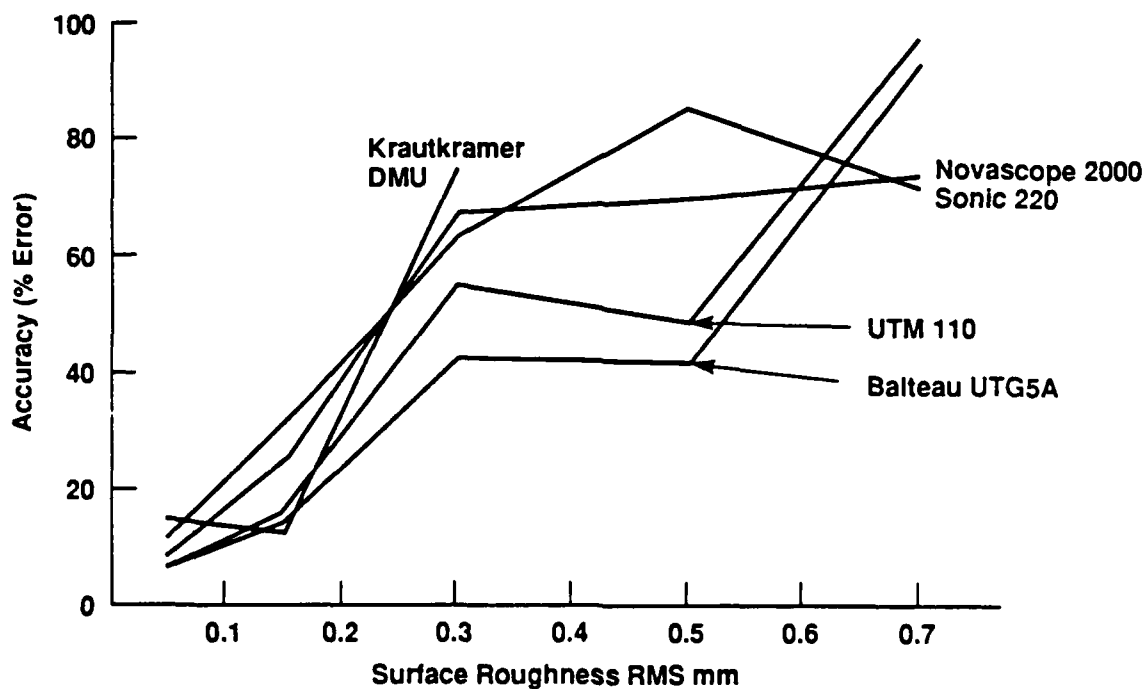


Figure 3. Measurement error for commercially available thickness gauges. Thickness measurement error increases with an increase in surface roughness (29).
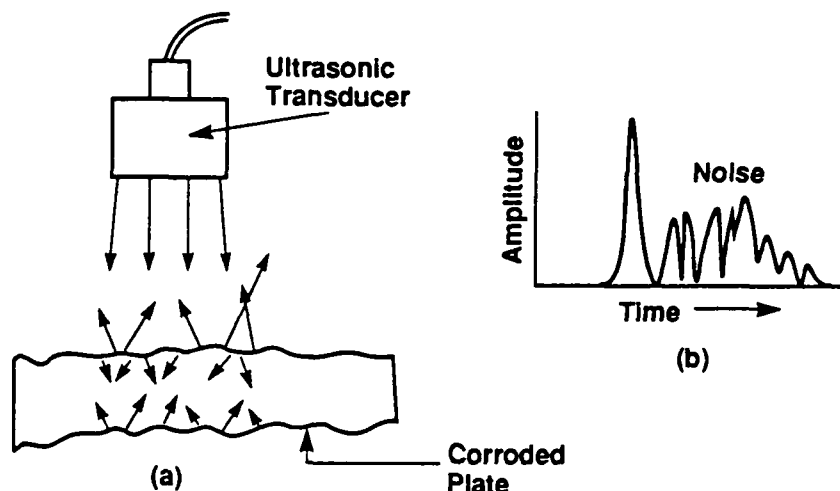
Figure 4. Thickness measurement of corroded plate using conventional ultrasonic method. (a) Scattering is caused by corroded surface. (b) Backsurface signal cannot be resolved in scattering-generated noise (29).

(see Figure 2) can be used to identify the front and back surface reflections for corrosion application.

When only one of the two surfaces is corroded, the transducer is placed on the smooth surface for good contact. When inspecting from the corroded (rough) side, a bubbler with a water column for coupling the ultrasound can be employed. Bubblers have an added advantage of using focused transducers to direct the beam inside the specimen and reduce the scattering noise (29). The focused transducer and bubbler combination can be used to a certain level of roughness; then their performance degrades, and errors in thickness measurement increase. Selection of an ultrasonic technique with increased surface roughness is summarized in Table 1.

Detection of hidden surface corrosion can also be performed by ultrasonics. In such a case, scattering caused by corrosion is used as an indicator of corrosion (6). With no corrosion, the ultrasonic reflected signals are well resolved and free of noise.

2   *Pitting Corrosion*

Inspection of components with pitting corrosion (pits greater than 2-mm diameter) is more difficult than generalized surface corrosion. An immersion transducer with a bubbler, as described earlier, could be used when pitting is only present on the surface opposite the transducer. The ultrasonic beam should be focused within the thickness of the specimen where the bottom of pits is expected. Beam focus reduces scattering from the surface, as the beam is incident in a small area. Another approach for such an application has been reported by Splitt (30). They have used a dual transducer where the ultrasonic beam incident on the bottom of the pit is reflected to the transducer.

Ultrasonics can also be used to measure pit depths. In such a case, a transducer that focuses the beam over the front surface is employed. The arrival time of the front-surface reflection is used to map the profile of the components.

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Table 1

APPLICATION OF ULTRASONIC TECHNIQUES TO MEASURE REMAINING
THICKNESS ON SAMPLES AFFECTED BY SURFACE CORROSION

| Surface Condition | | |
| --- | --- | --- |
| Inspection Side (in contact with the transducer) | Opposite Side | Ultrasonic Techniques |
| Smooth | Smooth | Digital Thickness Gauge |
| Smooth | Rough | Contact/Bubbler |
| Smooth | Extremely Rough | Bubbler with Focused Transducer |
| Rough | Smooth | Bubbler |
| Rough | Rough | Bubbler |
| Extremely Rough | Smooth | None of the Above |

Note:    Rough - pit depths less than 2 mm
Extremely rough - pit depth greater than 2 mm

### 3.  Cracking

Conventional crack-detection techniques are used to detect cracking in the form of IGSCC, SCC, or corrosion fatigue.  These techniques generally use refracted shear or longitudinal waves transmitted at an angle of 30 to 60 degrees.  The reflected signal from the crack indicates its presence.  Although conventional ultrasonic techniques are widely used, their performance is sometimes unsatisfactory.  For example, conventional methods are known to have low probabilities of detection for IGSCC in stainless steels.

Exfoliation is a form of cracking produced by corrosion.  Hagemaier (10) has reported a simple ultrasonic pulse-echo technique to detect corrosion around the fasteners in aircraft structures.  An ultrasonic transducer is placed at the periphery of the fastener holes, and the backwall signal is monitored.  Exfoliation in the holes obstructs the sound waves and results in a loss of backsurface signal.  This technique can be further improved by using focused transducer beams directed more toward the exfoliation damage.

### G.  Visual Inspection

Visual inspection is performed whenever the corroded surfaces are visible by sight or by using borescopes.  Many photographic examples of various forms of corrosion damage are found in Ref. (3).  Visual inspection is simple, fast, easy to apply, and usually low in cost.  Using this method, the inspection is performed on external surfaces of aircraft and also on internal areas which can easily be made accessible by the removal of access panels or equipment.  The accessibility of the inspected area can sometimes be extended by making use of mirrors and borescopes. An evaluation of the commercially available borescopes for visual inspection has been done by Light (31).  His study identified twelve types of borescopes that are commercially available.  Recently, fiber optics has been introduced to inspect through small openings (32).  Records of visual tests can be made in photographic cameras and video cameras.

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## 1. Surface Corrosion Inspections

For some inspections, paint can be removed in areas where its adhesion appears to be poor and corrosion seems to be located underneath. The same procedure applies to protective layers and sealants. The inspection aims at identifying the characteristic signs of corrosion such as change in color, bulges, cracks, and corrosion products. The evaluation is based on the outward appearance of damage and the type and composition of corrosion products.

## 2. Cracks

Large cracks can be detected by careful visual inspection. Hagemaier (33) has given examples of detecting SCC in aluminum landing-gear forgings, aluminum frame forgings, and steel main landing gear.

## 3. Pits

Visual inspection has been used to detect pitting corrosion in high-strength steel, main-landing-gear truck beams. Corrosion can occur in the four lubrication holes if the lubrication (grease) is not replaced at periodic intervals as specified by the aircraft maintenance manual. The pitting, if undetected, can result in stress corrosion.

Inservice inspection of these pits requires removal of the lubrication fitting and grease from each hole. The internal surface of each hole is checked using a 0-degree (forward-looking), 2.8-mm diameter endoscope, which is a high-quality medical borescope. If corrosion products or pitting are revealed, the hole is checked a second time with a 70- or 90-degree (side-view) endoscope. When pits are detected, the beam is removed from the aircraft and the pits are removed by oversizing the affected holes.

## IV. CORROSION DETECTION NEEDS

In the next few subsections, some of the corrosion NDE needs for specific branches of DoD are identified. While an effort was made to identify individual needs, some do overlap. For example, all three branches use helicopters that have the same corrosion problems.

Corrosion problems are usually given increased priority when they directly affect the safety, fleet readiness, and depreciation of value. Because of these factors, helicopters and aircraft have always been given prime importance with reference to corrosion. This was demonstrated when the USAF organized a workshop in "Nondestructive Evaluation of Aircraft Corrosion" in 1983 (12,34-38). Presentations during the conference were made by personnel from the Air Force, Army, and Navy to recommend research and development programs dealing with the detection of corrosion in aircraft.

Recognizing corrosion as a major area of interest, the three services started a literature database entitled Corrosion Information and Analysis Center (CORIAC). The CORIAC files can be accessed through the Metals and Ceramics Information Center (MCIC) database. Currently, the CORIAC files center has approximately 1000 records of information.

The following three subsections discuss the problems related to Army, Air Force, and Navy aircraft, respectively. Because of the overlap in the problems among the three services, it is recommended that all three subsections be read.

## A. Army Corrosion Problems

Corrosion problems for the Army occur in both helicopters and aircraft. The problems related to the aircraft are common to the Air Force and Navy and are covered in the subsection on Air Force problems.

Baker (36) from the Army Aviation R&D Command has given several examples of corrosion in helicopters. He addressed areas where a good NDE method could be used for field or department inspections. The major aircraft components affected were main-rotor mast extension, blade, and retention nut; pitch-change link; functional and nonfunctional main landing gears; and aircraft control tubes. He identified the need for an NDE method for thickness measurement of corrosion-protection coatings whose thickness can reduce with service. Another area in need of an NDE method is the control tubes. Water enters the control tubes, causing internal corrosion. The extent of such corrosion cannot be determined, and an NDE method is needed here. Unnecessary replacement of tubing is common on older aircraft where the amount of corrosion is unknown.

Schaffer and Lynch (39) have identified corrosion problems experienced in recent years that resulted in avionic failures. The avionic equipment that suffers the most from environmental effects are those mounted external to the airframe such as electronic countermeasure pods, photographic pods, antennas, and lights. Because of their exposure to moisture from rainstorms or low-level flights over water, they are targets for corrosion. Two prime examples of susceptibility to this condition are the clamshell doors on helicopters and radomes on fixed-wing aircraft. These doors and radomes leak extensively when the gaskets become worn or damaged.

After moisture or fluids enter an airframe or avionic compartment, it may follow a natural conduit directly into a sophisticated piece of avionic equipment. Hydraulic and fuel lines, control surface linkages, oxygen lines, waveguides, structural stringers, and electrical wire/cable runs act as natural conduits to moisture and fluids.

The avionic systems on aircraft are not isolated "black boxes" sealed against the environment. There are many compartments, switches, lights, relays, terminal boards, circuit-breaker panels,and so forth that make up a complete system. In addition, a sophisticated aircraft may contain miles of wire and coaxial cables and hundreds of electrical connectors. Corrosion attack on the various elements making up the total avionic system can create numerous problems in relation to reliability and maintainability.

## B. Air Force Corrosion Problems

A workshop on NDE of aircraft corrosion organized by the USAF in 1983 recognized the corrosion problems that needed immediate attention. The workshop presented an overview of the many types of corrosion problems encountered in practice. Teal (34) discussed NDE needed for corrosion detection. These included detection and determination of the extent of corrosion without disassembly; detection of corrosion in multiple layers, under sealant, and beneath paint; identification of suspected corrosion by scanning large areas; and severity of corrosion inspection in complex geometries (see Figure 5). He also presented successfully applied NDE methods for detecting corrosion, including detection of single-layer corrosion by ultrasonics, tubular corrosion by radiography, disbonds in honeycombs by ultrasonics, and moisture in honeycombs by acoustic emission.

Cooke and Meyer (37) identified corrosion problems in the Air Force and performed an assessment of the NDT methods (see Table 2). His assessment criterion for NDT methods is rated by their ability to determine, in the following decreasing order of importance, the extent of corrosion in the surface area (highest priority), severity of attack in depth, site corroding activity, rate of attack, and type of corrosion (lowest priority).
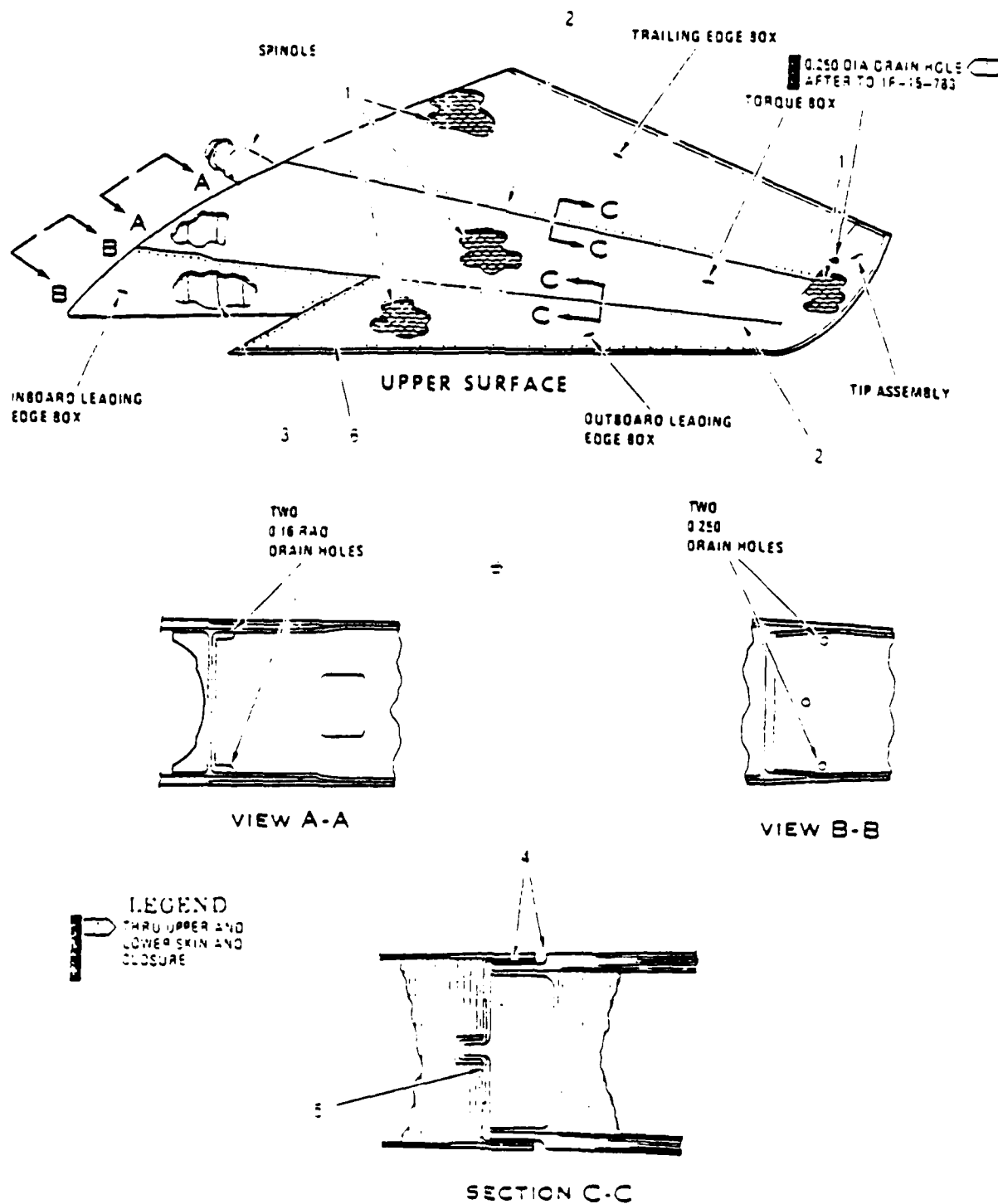
Figure 5. Stabilator corrosion-prone and critical items/areas [Ref. (34)]

## Table 2

## CORROSION DETECTION ASSESSMENT [Ref. (37)]

| Structure Type | Suggested Technique | Corrosion Assessment Characteristics | | | | | | Ease of Use | Availability | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (X-Y) Extent | (Z) Severity | Actively Corroding | Rate of Attack | Type of Corrosion | Portable | | 1-2 Years | 3-5 Years | >5 Years |
| A. Skin & Stringer | Double-wall x-ray | G | A | N/A | N/A | P | G | A | current x-ray | digital x-ray | |
| | Neutron radiography | G | A | G | N/A | P | P | A to P | | ✓ | |
| | Probe | P to G | P to G | G | G | N/A | N/A | : | P | A | |
| | Fiber optics | G | N/A | P | N/A | P | G | : | ✓ | | |
| B. Hollow Tubes | Horseshoe shaped probe | G | P | N/A | N/A | N/A | G | ( | ✓ | | |
| | Fiber optics | G | N/A | P | N/A | P | G | ( | ✓ | | |
| | Neutron radiography (N-ray) | | (See above under Part A.) | | | | | | | | |
| | Gamma attenuation | G | G | N/A | N/A | N/A | G | G to A | | | |
| C. Honeycomb | X-ray } N-ray | | (See above under Part A.) | | | | | | | | |
| | Harmonic Bond Tester | P to G | N/A | N/A | N/A | N/A | G | G | } current | | |
| | Ultrasonic NDI on Bond Line | P to G | N/A | N/A | N/A | N/A | G | G | | | |
| | IR Reflectivity w. chopped laser | G | A to P | ? | ? | A | G | A | | ✓ | |
| | Electrographic Photography | | | | (Limited application) | | | | | | |
| | Ultrasonic Bubbler | | (Limited application to bond integrity) | A | A to P | | | | ✓ | | |
| | Acoustic emission | P | P | A | A to P | N/A | A | A | } current | | |
| D. Circuit Boards | Imbedded probe | P to G | P to G | N/A | G | N/A | N/A | G | ✓ | | |
| | Signal harmonics | | (Limited application) | | | | | | ? | | |
| | Thermography | | (Used for QA in manufacturing) | | | | | | ✓ | | |

G = good, A = average, P = poor, N/A = not applicable

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Doruk (21) studied the kinds and causes of corrosion observed primarily in Type F-5A aircraft (see Figures 6 and 7). He reports cases of pitting corrosion in wing and fuselage skins and the drain-cavity section of jet-engine compressor casings (Inconel W), and crevice corrosion in areas adjacent to nonmetallic components such as fiberglass antennas. Exfoliation corrosion was present in the vertical stabilizer attach angle (combined with stress corrosion) (7075-T6), vertical stabilizer along the edge of the radome (combined with stress corrosion), and inside the air inlet ducts.

Stress corrosion cracking was detected in the wing-to-body joint fitting (7075-T6), main landing-gear uplock support rib (7075-T6), eye bolt of the landing-gear strut, and H-link connected to the landing gear strut (Figure 8). Bimetallic corrosion was found in holes in the vertical stabilizer attach angle, holes under the wings through which the jaw bolts were placed, holes in the magnesium alloy covering plates under the fuselage, wing skins adjacent to countersunk fastener heads, and access panels and covers of magnesium in contact with aluminum. Honeycomb assembly damage at the leading-edge sections of wings was detected.

Hardy and Holloway (38) have identified key technology needs for airframe corrosion. The items in the priority of ranking are:

1.  Faying Surface/Stackups: Rapid coverage of large areas, improved discrimination between defects and geometry changes, location of the layer containing the defect, and image damage (C-scan) (characterization of the extent) with provision for permanent records.

2a. A/C Wheels: Crack detection with paint on. (The polyurethane coating is being removed solely to facilitate penetrant inspections. Eddy current is specific to bead seat. A similar situation exists for baked resin coatings for low-temperature engine components and for coated landing gears. Rapid, full coverage is needed.) (The inspection technique must easily adapt to the different size rims that must be inspected.)
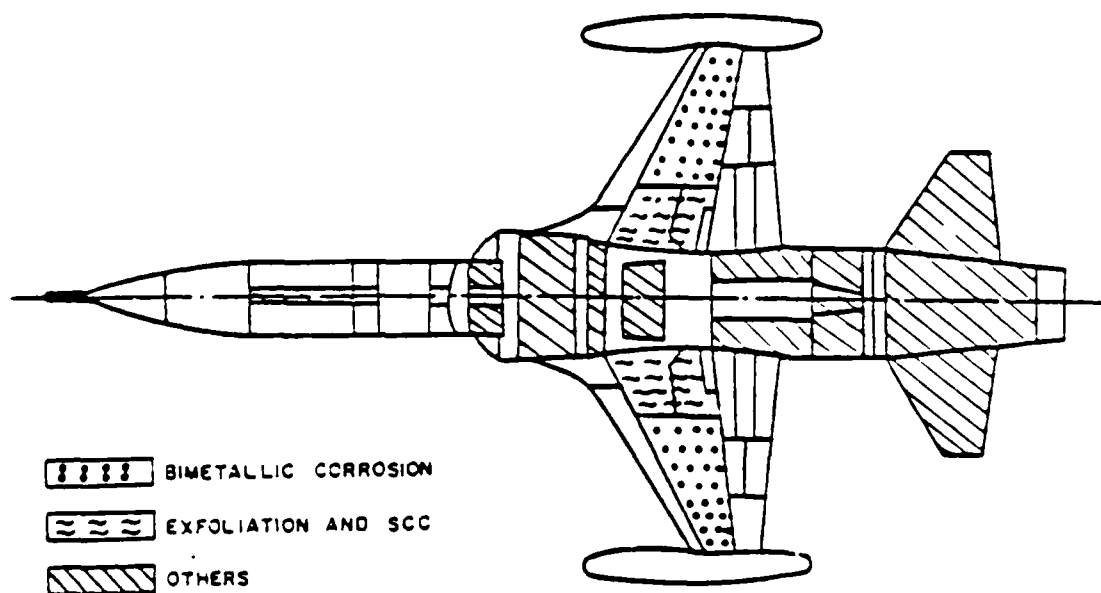


Figure 6. Locations of concentration of corrosion on the under section of the aircraft body (F-5A). [Exfoliation and stress-corrosion cracking indicated on the figure are those found on parts incorporating the landing gears (21).]
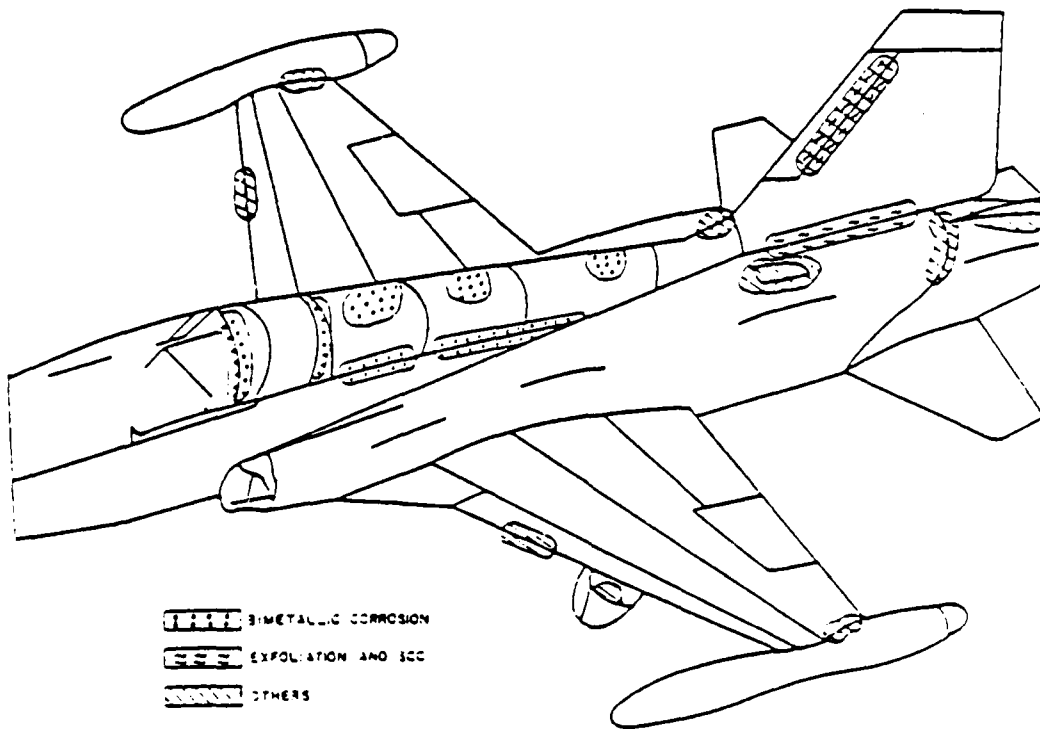
Figure 7. Locations of concentration of corrosion on the center and aft sections of the aircraft body (F-5A) (21)



Figure 8. Stress-corrosion crack in the H-link connected to the landing-gear strut, which was made visible using a fluorescent penetrant (21)

2b. Honeycomb Panels: Rapid coverage of large areas (e.g., large transports), image damage (C-scan), more realistic accept/reject criteria recorded, detection of face/core corrosion, fluid entrapment (closeout damage leads to water intrusion), and adaptable to complex geometry. (Infrared was suggested. Currently, visual and "con tap" methods are being used.)

3. Corrosion Around Fasteners: Provide rapid coverage of large areas (which areas require a second look?), provide indication of potential corrosion, establish detectability requirements, and provide inspection data for interpretation by structural engineers.

4. Quantification of Corrosion: Depth/area of corrosion (i.e., determine the extent of intergranular corrosion before grinding a component down by "brute force" past minimum acceptable thickness). (Should an electrochemical approach to used or early detection of corrosion?)

5. Measurement of Coating Adequacy: Remaining coating life (in original condition and after a repair), adequacy of application, and applicable to paints/primers/platings/ conversion coatings/ion-vapor-deposited (IVD) coatings/anodic coatings/etc. (Are the protective barriers broken?) (For example, the capability of current eddy current techniques is 0.005 mm to measure cadmium plating thickness on high-strength steel components due to magnetic permeability and electrical conductivity variations in plating and substrate. The question is: How can these variations be compensated for when the critical plating thickness required may be 0.008 mm? Signal averaging by a microprocessor may be one possible method to reduce such errors. Specifications for preservation systems and coatings are not applied as rigidly for replacement parts as they are for initial procurement. Uniform buy standards are needed.)

6. Munitions/War Readiness Material: Storage in "sealed" containers and potential application for corrosion probe. (How can stored munitions be inspected without removal from containers or, minimally, without disassembly?)

7. Corrosion Under Paint: Not a problem. (Filiform and corrosion under a sound coating system are not problems.)

8. Grinding Damage Under Platings (e.g., Chrome Plating): More discrimination for base-metal damage. (For example, sometimes techniques are too sensitive to grinding patterns without there being any damage in the base metal.)

9. Need for Standards, Qualified Inspectors Knowledgeable in Corrosion and Structural Mechanics, and Sufficient Equipment Appropriate for the Depot or ALC Level and for the Field Level.

To develop a suitable NDT technique for corrosion detection, the USAF funded a project (22) in 1984. The objective of this project was to develop nondestructive evaluation techniq· es for locating and characterizing corrosion hidden in aluminum alloy airframe structures. The candidate NDT techniques were realtime x-ray, realtime neutron radiography, and low-frequency eddy current (22). The Air Force is now in the process of funding another NDT project in new corrosion NDT techniques in fiscal year 1988. Hardy and Holloway (38) have reported key needs in technology for corrosion detection.

## C. Navy Corrosion Problems

Navy's corrosion problems are intensified by their close association with seawater. The Navy's aircraft are exposed to the salt and moisture and, therefore, corrode more than their counterparts in the Air Force.

In an effort to control the corrosion problem, the Navy washes all squadron aircraft every 14 days. The Navy also inspects their aircraft for intergranular, galvanic, filiform, pitting, and surface corrosion. Some of the examples of corrosion and the applied inspection methods are as follows (35) (see Figures 9, 10, and 11).

Holland, from Naval Air Systems Command (35), has cited some of the current NDT test procedures (see Table 3). In most cases, components must be removed for aircraft to be examined. Corrosion must also be at a fairly advanced stage before it is detectable. The currently used equipment is manually operated, is subject to operator interpretation, and lacks permanent records. Certain cases also require pain stripping. Because current inspection methods are very slow, the inspections are usually limited to small areas. NDT methods and systems are, therefore, required to overcome the above limitations. The Navy is also interested in pursuing work in methods to detect interface corrosion, corrosion under paint, automatic corrosion mapping, realtime radiography, neutron radiography, and phase-sensitive eddy current for far-side corrosion.

Hollingshead and Hanlan (40) have emphasized the role of corrosion training in combating corrosion. Increased personnel awareness of elementary fundamentals improved the chances for preventing corrosion. A summary of the corrosion problems in the Canadian naval fleet follows (40).



| ZONE NO | DESCRIPTION |
|---|---|
| 1 | LH Forward Pylon |
| 3 | Tunnel |
| 4 | Canted Deck |
| 5 | LH Stubwing |
| 7 | Nose |
| 8 | LH Aft Pylon |
| 14 | LH Fuselage |
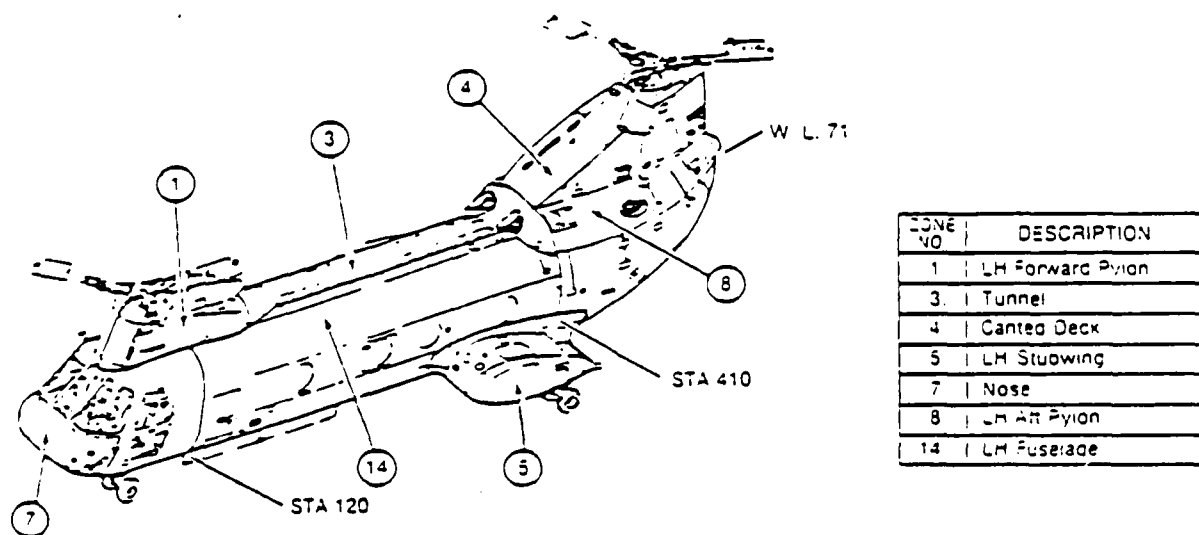
Figure 9. Identification of inspection zones -- H-46 [Ref. (35)]

Figure 10. Stabilator main-box upper skin and lower skin [Ref. (35)]

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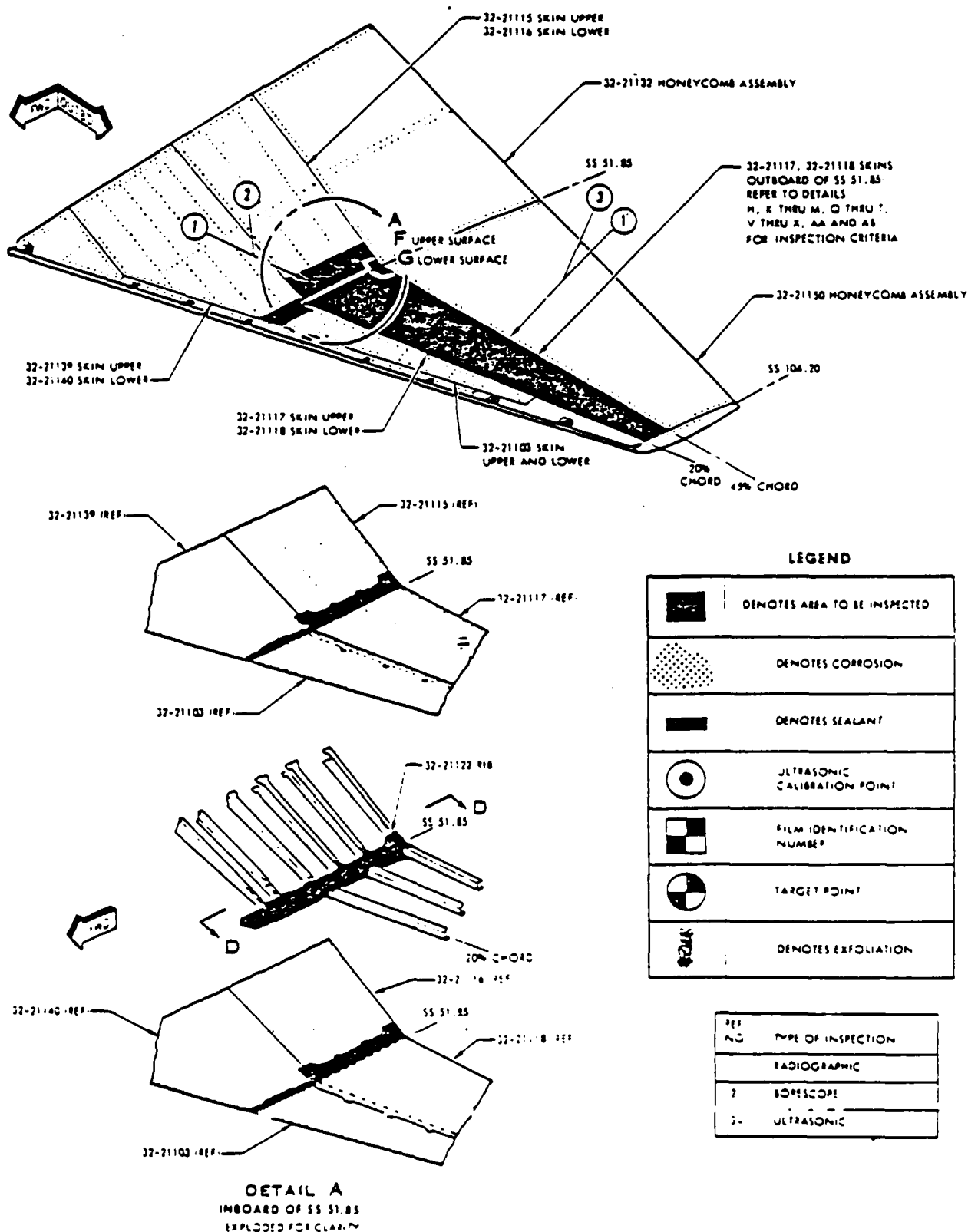
Figure 11.  Stabilator main-box upper skin, lower skin, and rib [Ref. (35)]

Table 3

CORROSION EXAMPLES AND NDE METHODS APPLIED [Ref. (35)]

| Components | NDT Method | Type of Corrosion | Corrosion-Proof Areas |
|---|---|---|---|
| 1. H-46 Rotor Blade | X-Ray | Galvanic | Spar Back Wall, Interior of Spar, STA 286 |
| 2. H-46 Engine Exhaust Device | Ultrasonics | Galvanic | Mounting Flange |
| 3. H-46 Stub Wing | Eddy Current | Multiple Mechanisms | Stub-Wing Fittings |
| 4. H-46 - H-53 Device Shaft | Ultrasonics | Exfoliation | Drive Shaft |
| 5. Landing Gear on Navy Aircraft | Ultrasonics | Exfoliation/ Pitting | Inside of Telescopic Mechanism |
| 6. F-4 Stabilizer Rib | X-Ray | Intergranular | Center Rib |
| 7. H-4 Stabilizer Skin | X-Ray and Ultrasonics | Exfoliation | Skin |
| 8. H-1 and H-2 Main Rotor Blade | Ultrasonics and Harmonic Band Tests | Pitting | Doubles and Span |

D. Conclusions

A number of NDE methods for detection and evaluation of corrosion are presently available. While these methods can be applied for a number of corrosion inspection problems, a large number of areas are still too difficult or too expensive to inspect. Inspections can only be justified if their costs are lower relative to the replacement costs. From the available information, the conclusion can be reached that the present corrosion NDE methods are not sufficient to fulfill the demands of the Army, Air Force, and Navy. This report also notes that the corrosion problems of the DoD services overlap and are common in several cases. To address these needs, a cooperative effort should be established to develop and improve NDE methods for corrosion evaluation.

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### 3.0 COORDINATION MEETINGS/SITE VISITS

# 3.0 COORDINATION MEETINGS/SITE VISITS

**RTA Coordination Meetings/Site Visits**
**"NDI Oriented Corrosion Control for Army Aircraft:**
**Phase I Inspection Methods"**

At AVSCOM DERSO/CCAD:    November 17, 1987
                         January 31 - February 1, 1988
                         March 3-6, 1988
                         July 18-21, 1988

At AVSCOM-St. Louis:     December 1, 1987
                         January 26-27, 1988
                         June 13-14, 1988
                         September 19-20, 1988
                         November 10-11, 1988
                         March 20-21, 1989

At RTA:                  April 28-30, 1988
                         September 13, 1988
                         October 25, 1988
                         November 1, 1988
                         January 19, 1989
                         February 16-18, 1989
                         March 1-2, 1989
                         April 5-6, 1989

At Bell Helicopter       September 25-27, 1988
   Textron, Fort Worth, Texas

**SwRI Coordination Meetings/Site Visits**
**"NDI Oriented Corrosion Control for Army Aircraft:**
**Phase I Inspection Methods"**

At AVSCOM DERSO/CCAD:    July 20-21, 1988

At RTA-Chicago, IL       June 28, 1987
                         February 16, 1989
                         June 6, 1989

At SwRI/San Antonio, TX  April 22, 1987
                         May 9, 1989

# 4.0 IMPROVED STORAGE METHODS OF PARTS
## AT CCAD WORK CENTERS

# 4.0 IMPROVED STORAGE METHODS OF PARTS
## AT CCAD WORK CENTERS

**RTA**   **Reliability Technology Associates**
700 Ravinia Place
Orland Park, IL 60462-3750
(312) 349-9590

December 10, 1987

Mr. Laurence A. Davis
Depot Engineering & RCM Support Office
U.S. Army Aviation Systems Command
Corpus Christi Army Depot
ATTN: AMSAV-MR (MS 55)
Corpus Christi, TX 78419-6195

Subject:   AVSCOM Corrosion Control Program Item 13
           (RTA Project 1)
           "Improved Storage Methods of Parts at CCAD Work Centers"

Reference:   SwRI Subcontract No. 19359 (Pending)
             Mod. P00076 on Contract No. DLA 900-84-C-0910
             "NDI Oriented Corrosion Control for Army Aircraft:
             Phase I. Inspection Methods" - Task 1

Dear Larry:

The purpose of this letter is to provide corrosion control recommendations, through the U.S. Army Aviation Systems Command Depot Engineering & RCM Support Office (DERSO), to the Director of Supply at Corpus Christi Army Depot (CCAD) regarding certain carts on which many parts are stored at CCAD. These recommendations are based on on-site visits to CCAD on September 24, 1987, and November 17, 1987, and a review of the corrosion problem with DERSO personnel, particularly Newman P. Bulloch, material engineer.

The background of the corrosion problem is as follows. CCAD has a large number of yellow carts. The two shelves on the carts are wood, but the shelves are held in place by steel racks. These racks were painted several years ago, but the paint has worn away leaving bare steel areas. Although the carts were obviously originally intended to be used primarily for transportation of parts throughout the depot, there has been a tendency in recent years to use the carts to store parts for some period of time. When magnesium castings are stored on the carts, they frequently touch the bare steel areas on the racks. This initiates galvanic corrosion in the magnesium castings. What is required, then, is some form of coating to cover the steel structure or another method of isolating the magnesium from the steel racks.

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Corrosion control recommendations regarding these carts are as follows. All loose paint should be removed from the steel racks; the metal should be cleaned and degreased. Then, two coats of corrosion resistant primer MIL-P-23377 Type II should be applied. Each coat should be 0.3 to 0.6 mil thick (0.6 to 1.2 mil total primer thickness). At last 30 minutes, and preferably 60 minutes or more, should be allowed between applications of the two primer coats. After primer application (at least 30 minutes after - 60 minutes is better), a top coat of epoxy MIL-C-22750 should be applied. This, then, should solve this corrosion problem.

If you have any questions on this, please contact me at (312)349-9590.

Sincerely,

*Dan Henry*

C. D. (Dan) Henry III, PhD, PE

cc: George Matzkanin, SwRI

# 5.0 ESTABLISH DATA CONCERNING ENVIRONMENTAL PARAMETERS – CORROSION FACTOR

## 5.0  ESTABLISH DATA CONCERNING ENVIRONMENTAL PARAMETERS – CORROSION FACTOR

**RTA**  Reliability Technology Associates
700 Ravinia Place
Orland Park, IL 60462-3750
(312) 349-9590

March 15, 1988

Mr. Laurence A. Davis
Depot Engineering & RCM Support Office
U.S. Army Aviation System Command
Corpus Christi Army Depot
ATTN:  AMSAV-MR (MS 55)
Corpus Christi, TX 78419-6195

Subject: AVSCOM Corrosion Control Program Item 23
(RTA Project 2)
"Establish Data Concerning Environmental Parameters –
Corrosion Factor"

Reference:  SwRI Subcontract No. 19359
Mod. P00076 on Contract No. DLA 900-84-C-0910
"NDI Oriented Corrosion Control for Army Aircraft:
Phase I.  Inspection Methods" – Task 1

Dear Larry:

The purpose of this letter is to report on the results of RTA's efforts on the subject project.  The objective of the project is to establish environmental corrosion parameters designating relative degree of corrosion intensity for areas where U.S. Army aircraft are located.

The approach taken was to adapt the Air Force's PACER LIME environmental corrosion severity classification system for U.S. Army Aviation use. Information on the PACER LIME system was obtained from publication AFWAL-TR-80-4102 Part I, "PACER LIME:  An Environmental Corrosion Severity Classification System" by Robert Summitt and Fred T. Fink, August 1980, and publication AFWAL-TR-86-4074, "Corrosion Maintenance and Experimental Design" by Robert Summitt, January 1987, as well as telephone conversations with Robert Summitt of Michigan State University, principal investigator of the PACER LIME effort, and Fred H. Meyer of the Air Force Wright Aeronautical Laboratories Materials Laboratory.

Based on a consideration of existing literature on materials degradation and environmental factors, the PACER LIME system relates expected corrosion damage at a location to proximity to salt or sea; moisture factors (humidity, rainfall); and pollutant concentrations (sulfur dioxide, particulates, ozone). The environmental factors for a location are compared to either of two sets of critical threshold values for the factors.  These two sets of critical threshold values are shown in Attachment I.  The PACER LIME system reports its expected corrosion damage results for a location in terms of a four-step rating (AA,A,B,C) and generally reports two ratings for a location, one based on each set of critical threshold values.

In adapting the PACER LIME system for U.S. Army Aviation use, RTA has combined the two sets of critical threshold values into a ten-step rating scheme for U.S. Army aircraft deployment locations. The decision logic which leads a location to be classified with an expected corrosion damage rating (ECDR) of from 1 to 10 (with 10 the most corrosive environment) is given in Attachment II.

Publication AFWAL-TR-80-4102 Part I has environmental data for U.S. Air Force, Air Force Reserve, and Air National Guard airbases. Humidity and rainfall data are taken from U.S. Air Force Environmental Technical Application Center (ETAC) worldwide airfield climatic data; ambient pollutant concentrations are taken from U.S. Environmental Protection Agency (EPA) annual air quality statistics. Publication AFWAL-TR-86-4074 has environmental corrosion severity classifications for all sites in the United States where Blackhawk helicopters are located; these environmental corrosion severity classifications can be translated into ECDRs. From these data RTA was able to come up with ECDRs for all U.S. Army aircraft deployment locations in the United States. This listing is given in Attachment III.

The ECDRs show the relative degree of corrosion intensity for an area. With the current level of knowledge of materials degradation and environmental factors, it is not possible to come up with a rating giving the proportional degree of corrosion intensity of a location, i.e., it is not valid to assume that an area with four times the ECDR of another will corrode parts four times as quickly. However, considerable research is being carried out in this area by the Air Force and the EPA and it may be possible in a couple years to proportionally compare one environment with another one.

Originally it was intended to include areas outside the United States in the rating scheme. However, although weather factors data are available from ETAC worldwide, pollutant data are not generally available for areas outside the United States. The problem is that no single agency, like the EPA, compiles and publishes data in a standard format. Collecting the data required to apply the decision logic to locations outside the United States would be a major undertaking.

In summary, then, RTA has established environmental corrosion parameters, called expected corrosion damage ratings (ECDRs), designating the relative degree of corrosion intensity for areas in the United States where U.S. Army aircraft are located.

If you have any questions on this, please contact me at (312)349-9590.

Sincerely,

Dan Henry

C. D. (Dan) Henry III, PhD, PE

Attachments

cc: George Matzkanin, SwRI

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## ATTACHMENT I

## Critical Threshold Values

| Ambient Factors | Annual Mean | |
|---|---|---|
| | I | II |
| Suspended particulates ($\mu g/m^3$) | 61 | 86 |
| Sulfur dioxide ($\mu g/m^3$) | 43 | 72 |
| Ozone ($\mu g/m^3$) | 36 | 47 |
| Absolute humidity ($g/m^3$) | 7.1 | 9.0 |
| Proximity to sea or salt source (km) | 4.5 | 2 |
| Rainfall (cm total) | 125 | 150 |

ATTACHMENT II.

Expected Corrosion Damage Rating (ECDR) Decision Logic

START

IS DISTANCE TO SEA OR SALT SOURCE <4.5km ?

IS DISTANCE TO SEA OR SALT SOURCE <2.0 km ?

IS ABSOLUTE HUMIDITY >9.0g/m³ ?

IS TOTAL ANNUAL RAINFALL >150cm ?

IS SULFUR DIOXIDE >72µg/m³ ?

ARE TOTAL SUSPENDED PARTICULATES >86µg/m³ ?

IS OZONE >47µg/m³ ?

IS ABSOLUTE HUMIDITY >7.1g/m³ ?

IS TOTAL ANNUAL RAINFALL >125cm ?

IS SULFUR DIOXIDE >43µg/m³ ?

ARE TOTAL SUSPENDED PARTICULATES >61µg/m³ ?

IS OZONE >36µg/m³ ?

ECDR = 1
ECDR = 2
ECDR = 3
ECDR = 4
ECDR = 5
ECDR = 6
ECDR = 7
ECDR = 8
ECDR = 9
ECDR = 10

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# ATTACHMENT III
## Expected Corrosion Damage Ratings (ECDR)
## for U.S. Army Aircraft Deployment Locations (U.S.)
### (NG - National Guard, AR - Army Reserve)

| Location | ECDR | Location | ECDR |
|---|---|---|---|
| **ALABAMA** | | **DELAWARE** | |
| Fort Rucker | 8 | Greater Wilmington Airport (NG) | 7 |
| Montgomery (NG) | 4 | | |
| St. Clair Co. Airport (AR) | 8 | **FLORIDA** | |
| Anniston Army Depot | 4 | | |
| Birmington Muni Airport (NG) | 8 | Craig Field Municipal Airport, Jacksonville (NG) | 10 |
| Redstone Arsenal | 8 | | |
| Bates Field, Mobile (NG) | 10 | Orlando Jetpt (AR) | 4 |
| | | McDill AFB (Readiness Command) | 10 |
| **ALASKA** | | Opalocka Airport (AR) | 6 |
| Fort Richardson | 2 | **GEORGIA** | |
| **ARIZONA** | | Fort Gordon | 6 |
| | | Winder-Barrow (NG) | 4 |
| Phoenix (NG) | 6 | Dobbins AFB (NG, AR) | 4 |
| Fort Huachuca | 2 | Charlie Brown Airport, Atlanta | 4 |
| Yuma Proving Grounds | 4 | Fort Stewart | 6 |
| | | Fort Benning | 4 |
| **ARKANSAS** | | | |
| | | **HAWAII** | |
| Camp Robinson (NG) | 6 | | |
| Adams Field (AR) | 6 | Hawaii | 10 |
| **CALIFORNIA** | | **IDAHO** | |
| Los Alamitos AFRC | 8 | Boise Muni Airport (NG) | 1 |
| Fort Ord | 7 | | |
| Edwards AFB | 4 | **ILLINOIS** | |
| Fresno Airport (NG) | 8 | | |
| Hamilton AFB | 4 | Decatur Airport (NG) | 6 |
| Stockton Metro Airport (NG) | 8 | Midway Airport, Chicago (NG) | 4 |
| Mather AFB (NG) | 8 | Gleview NAS (Fort Sheridan) | 4 |
| Sierra Army Depot | 2 | Scott AFB (AR) | 6 |
| Fort Irwin | 4 | Parks Bi-State Airport, Cahokia (Granite City Army Depot) | 6 |
| **COLORADO** | | | |
| | | **INDIANA** | |
| Fort Carson | 4 | | |
| Buckley ANGB | 4 | Shelby Co. Airport (NG) | 4 |
| | | Indianapolis Intl. Airport (Fort Benjamin Harrison) | 4 |
| **CONNECTICUT** | | | |
| Groton/New London Airport (NG) | 10 | | |
| Bradley Intl. Airport (NG) | 2 | | |

ATTACHMENT III (Cont'd)
Expected Corrosion Damage Ratings (ECDR)
for U.S. Army Aircraft Deployment Locations (U.S.)
(NG - National Guard, AR - Army Reserve)

| Location | ECDR | Location | ECDR |
|---|---|---|---|
| **IOWA** | | **MICHIGAN** | |
| Davenport Muni Airport (NG) | 4 | Abrams Muni Airpot, Grand Ledge (NG) | 1 |
| Waterloo Muni Airport (NG) | 4 | Selfridge ANGB (AR) | 1 |
| Boone Airport (NG) | 4 | Oakland Pontiac Airport (TACOM) | 2 |
| Des Moines Muni Airport (AR) | 4 | | |
| **KANSAS** | | **MINNESOTA** | |
| Fort Riley | 3 | Downtown Airport, St. Paul (NG, AR) | 2 |
| Olathe (AR) | 3 | | |
| Forbes AFB (NG) | 3 | **MISSISSIPPI** | |
| **KENTUCKY** | | Key Field, Meridian (NG) | 4 |
| Capital City Airport, Frankfort (NG) | 6 | Hawkins Field, Jackson (NG) | 4 |
| | | Vicksburg Muni Airport (AR) | 4 |
| Fort Knox | 6 | Gulfport Muni Airport (NG) | 10 |
| Fort Campbell | 4 | CD Lemmons Muni Airport, Tupelo (NG) | 4 |
| Bowman Field, Louisville (AR) | 6 | | |
| **LOUSIANA** | | **MISSOURI** | |
| Lakefront Airport, New Orleans (NG) | 9 | Fort Leonard Wood | 6 |
| | | Springfield Muni Airport (NG) | 6 |
| Acadiana Regional Airport, New Iberia (AR) | 8 | Memorial Airport, Jefferson City (NG) | 6 |
| Fort Polk | 4 | Whiteman AFB (NG) | 3 |
| **MAINE** | | **MONTANA** | |
| Bangor Intl. Airport (NG) | 2 | Helena Muni Airport (NG) | 1 |
| **MARYLAND** | | **NEBRASKA** | |
| Phillips AAF (Aberdeen Proving Grounds) | 6 | Lincoln Airport (NG) | 2 |
| Weide AAF (Aberdeen Proving Grounds) (NG) | 6 | **NEVADA** | |
| Fort George Meade | 6 | Reno-Stead Airport (NG) | 4 |
| Hagerstown Muni Airport (AR) | 6 | **NEW HAMPSHIRE** | |
| **MASSACHUSETTS** | | Concord Muni Airport (NG) | 1 |
| Fort Devens | 1 | | |
| Otis ANGB (NG) | 2 | | |
| Westover AFB (NG) | 1 | | |

ATTACHMENT III (Cont'd)
Expected Corrosion Damage Ratings (ECDR)
for U.S. Army Aircraft Deployment Locations (U.S.)
(NG - National Guard, AR - Army Reserve)

| Location | ECDR | Location | ECDR |
|---|---|---|---|
| **NEW JERSEY** | | **OKLAHOMA** | |
| Morristown Muni Airport (Armament Research and Development Command) | 2 | Gen Howell Muldrow Airport, Lexington (NG) | 2 |
| Picatinny Arsenal Heliport (NG) | 2 | Max Westheimer Airport, Norman (AR) | 2 |
| Mercer Co. Airport (NG) | 6 | Fort Sill | 6 |
| McGuire AFB (Fort Dix) | 2 | Tulsa Intl Airport (NG) | 2 |
| Lakehurst NAS (ERADCOM Test Flight Activity) | 2 | | |
| | | **OREGON** | |
| **NEW MEXICO** | | McNary Field, Salem (NG, AR) | 4 |
| Santa Fe Muni Airport (NG) | 4 | **PENNSYLVANIA** | |
| Hollman AFB | 2 | | |
| | | Washington County Airport (NG, AR) | 4 |
| **NEW YORK** | | Muir AAF (NG) | 3 |
| | | Chambersburg Muni Airport (Depot Systems Command) | 3 |
| Niagara Falls Muni Airport (NG) | 2 | Willow Grove NAS (AR) | 6 |
| Hancock Field, North Syracuse (AR) | 4 | | |
| Albany Co. Airport (NG) | 4 | **RHODE ISLAND** | |
| Stewart Airport, Newburgh (USMA) | 2 | Quonset Airport, North Kingston (NG) | 10 |
| Long Island McArthur Airport Hgr A (NG) | 2 | | |
| Fort Drum | 2 | **SOUTH CAROLINA** | |
| Seneca Army Depot | 4 | | |
| | | McEntire ANGB | 4 |
| **NORTH CAROLINA** | | Columbia Metro Airport (Fort Jackson) | 4 |
| Rowan Co. Airport, Salisbury (NG) | 4 | | |
| Raleigh-Durham Airport (NG) | 6 | **SOUTH DAKOTA** | |
| Fort Bragg | 6 | Rapid City Regional Airport (NG) | 4 |
| **NORTH DAKOTA** | | | |
| Bismarck Muni Airport (NG) | 4 | **TENNESSEE** | |
| **OHIO** | | Smyrna Airport (NG) | 8 |
| | | McGee-Tyson ANGB | 6 |
| Lorain Co. Regional Airport (AR) | 4 | | |
| Akron-Canton Airport (NG) | 4 | | |
| Don Scott Field (Ohio State University) (NG) | 6 | | |
| Columbus Muni Airport (AR) | 6 | | |

ATTACHMENT III (Cont'd)
Expected Corrosion Damage Ratings (ECDR)
for U.S. Army Aircraft Deployment Locations (U.S.)
(NG - National Guard, AR - Army Reserve)

| Location | ECDR | Location | ECDR |
|---|---|---|---|
| **TEXAS** | | **WEST VIRGINIA** | |
| | | | |
| Dallas NAS (NG, AR) | 6 | Wood City Arpt (NG) | 2 |
| Hooks Airport (AR) | 6 | | |
| Easterwood Fld, College Station (AR) | 6 | **WISCONSIN** | |
| Fort Hood | 8 | Truax Field, Madison (NG) | 1 |
| R. E. Mueller Muni Airport, Austin (NG) | 8 | West Bend Airport (NG) | 1 |
| | | Waukesha Airport (AR) | 1 |
| Ellington AFB (NG) | 8 | | |
| Martindale AAF (NG) | 6 | **WYOMING** | |
| Randolph AFB (Fort Sam Houston) | 8 | | |
| San Antonio Int. Airport (AR) | 6 | Cheyenne Muni Airport (NG) | 1 |
| Kelly Heliport (Fort Sam Houston Medical) | 6 | | |
| Fort Bliss | 4 | **PANAMA CANAL ZONE** | |
| New Braunfels Airport (Fort Sam Houston Maintenance) | 6 | Albrook AFS | 10 |
| NAS Corpus Christi | 10 | **PUERTO RICO** | |
| | | | |
| **UTAH** | | Isla Grande Airport | 10 |
| | | Christiansted St. Croix, VI | 10 |
| Salt Lake City Intl Airport (AR) | 4 | Fort Buchanan | 9 |
| Airport #2, West Jordan (NG) | 4 | | |
| Dugway Proving Grounds | 4 | | |
| | | | |
| **VERMONT** | | | |
| | | | |
| Burlington Intl Airport (NG) | 4 | | |
| | | | |
| **VIRGINIA** | | | |
| | | | |
| Fort Belvoir | 5 | | |
| Byrd Intl Airport, Sandston (NG) | 6 | | |
| Petersburg Muni Airport (TRADOC) | 10 | | |
| Langley AFB (TRADOC) | 10 | | |
| Fort Eustis | 8 | | |
| | | | |
| **WASHINGTON** | | | |
| | | | |
| Snohomish Co. Paine Field (AR) | 6 | | |
| Fort Lewis | 2 | | |
| Spokane Intl Airport (NG) | 4 | | |

# 6.0   DEVELOPMENT OF IMPROVED AACE PI THRESHOLD VALUES

# 6.0 DEVELOPMENT OF IMPROVED AACE PI THRESHOLD VALUES

DEVELOPMENT OF IMPROVED
AACE PI THRESHCLD VALUES

Prepared for:

Depot Engineering & RCM
Support Office
U.S. Army Aviation Systems Command
Corpus Christi, Texas 78419-6195

Prepared by:

Reliability Technology Associates
700 Ravinia Place
Orland Park, Illinois 60462-3750

September 1988

# FOREWORD

The work described herein was performed for the U.S. Army Aviation Systems Command (AVSCOM), Depot Engineering and RCM Support Office (DERSO), as part of AVSCOM's program to assess the extent of corrosion in Army aircraft and its cost, investigate non-destructive inspection (NDI) techniques for corrosion, and formulate specific recommendations for detecting corrosion in new and fielded Army aircraft. The purpose of this specific effort was to develop an improved profile index (PI) threshold value for each aircraft in AVSCOM's aircraft analytical corrosion evaluation (AACE) program. It was conducted as part of a Special Task under the auspices of the Nondestructive Testing Information Analysis Center (NTIAC) at Southwest Research Institute (SwRI) under Contract No. DLA900-84-C-0910, CLIN 0001BM. This study was performed under subcontract by Reliability Technology Associates (RTA). At RTA, the program manager was Dr. Daniel Henry and the principal investigator was Mr. Douglas C. Brauer. Dr. Frank A. Iddings was SwRI's technical monitor for the study. At AVSCOM, this study was monitored by Mr. Curtis Young, who provided the necessary data and other information used as input.

# EXECUTIVE SUMMARY

This report presents the results of a Reliability Technology Associates (RTA) study to derive profile index (PI) threshold values, using statistical analysis procedures, for the various aircraft types participating in the Army's aircraft analytical corrosion evaluation (AACE) program. Closely related to AACE is the airframe condition evaluation (ACE) program which defines threshold values for each participating Army aircraft type based on a structural evaluation. The PI threshold value identifies those aircraft which are candidates for depot maintenance and every year a threshold is set for each aircraft type in the ACE/AACE program. Below are listed the 1986 AACE threshold values and the 1987 candidate values derived during this study.

| Aircraft Type | 1986 PI Threshold Value | 1987 Candidate Threshold Value |
|---|---|---|
| AH-1 | 125 | 134 |
| CH-47 | 125 | 136 |
| CH-54 | 125 | 127 |
| OH-6 | 125 | 127 |
| OH-58 | 125 | 133 |
| OV-1/RV-1 | 125 | 127 |
| U-21/RU-21 | 125 | 127 |
| UH-1M | 125 | 131 |
| UH-1H/V | 125 | 132 |
| UH-60 | 125 | 127 |

Although the primary goal of this study was to establish candidate 1987 AACE thresholds for the applicable aircraft types, an improved threshold evaluation methodology (ITEM) evolved as a result of looking at historical ACE/AACE data and probing into the origin of its derivation. The objective of ITEM is to provide a statistically-based method for defining/revising aircraft ACE and/or AACE profile index thresholds. Although the historical threshold data immediately available for use with ITEM may lack clear statistical significance, the methodology itself provides a rational basis for ensuring that future established aircraft PI thresholds are statistically well-founded and defensible.

ITEM is for revising existing threshold values based on the results of a threshold survey or from analysis of profiling data. It provides a means for defining either the number of aircraft to be evaluated as part of the survey or the range of PIs within the profiling data to be analyzed; both options are based on a maximum acceptable error of the true threshold estimate. This routine is intended to be applied annually to revise individual aircraft thresholds.

The underlying assumption for ITEM is that there exists a true threshold which is estimated annually by the threshold set. The true threshold is the mean of the universal population of historical thresholds (for a given aircraft) which are distributed normally. Bayesian statistics are used to derive an estimate (or current year aircraft threshold) of the true threshold by combining prior information with direct sample evidence. The prior and sample data are assumed to be from the same universal population. The threshold value derived is then tested for acceptability as an estimator of the true threshold.

ITEM is designed to provide well-defined engineering thresholds. It is

intended to eliminate, or reduce, aircraft fleet underreadiness (poor combat availability) and overreadiness (excessive maintenance costs). ITEM provides the "engineering" threshold. Typically a "management" threshold is also likely to be set which reflects budgetary contraints on the number of aircraft which can be returned to the depot annually. The difference between these two thresholds is often referred to as the "readiness gap."

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## 1.0 INTRODUCTION

This report presents the results of a Reliability Technology Associates (RTA) study to derive 1987 candidate profile index (PI) threshold values, using statistical analysis procedures, for each aircraft participating in the Army's aircraft analytical corrosion evaluation (AACE) program. This involved gathering historical AACE data, as well as airframe condition evaluation (ACE) data. ACE is closely related to AACE and is part of the same overall program. This historical data provided the basis for deriving statistically founded 1987 candidate threshold values.

As an outgrowth of the work performed during this study, an improved threshold evaluation methodology (ITEM) was defined. ITEM is a statistically based technique for deriving or revising ACE or AACE threshold values. It consists of a routine for revising existing ACE/AACE threshold values via annual profiling data or threshold survey data.

Following this introductory section, Section 2.0 presents the procedure, formulae, and underlying assumptions used in the routine for determining the 1987 candidate AACE PI threshold value for the various aircraft types in the program. Also presented are the PI threshold values derived using the routine. Section 3.0 presents the procedure, formulae and underlying assumptions used in ITEM. Section 4.0 provides several conclusions and recommendations relative to the use of ITEM. Completing this report are three appendices. Appendix A contains various pertinent statistical tables, Appendix B identifies the reference documents which supported the development of ITEM, and Appendix C provides the AACE PI threshold calculations.

## 2.0 DETERMINATION OF 1987 AACE PI THRESHOLD VALUES

ITEM is a statistically-based technique for defining PI threshold values. It consists of two routines which are defined in the following subsections.

### 2.1 Description of Routine

Described in this subsection is the routine that was used to establish candidate individual 1987 AACE PI threshold values for the AH-1, CH-47, CH-54, OH-6, OH-58, OV-1/RV-1, U-21/RU-21, UH-1M, UH-1H/V, and UH-60 aircraft. This involved calculating an individual threshold value for each aircraft and then determining its acceptability, adjusting the value, if necessary, to make the value acceptable.

Inherent within this routine are several assumptions which are necessary to support the application of the statistical concepts employed. These include the following.

1. There exists a universal population of historical PI threshold values for each aircraft. The mean of this population is the true threshold.
2. The population of PI threshold values for each aircraft is normally distributed.
3. The Student-t distribution approximates the normal distribution for small sample sizes (i.e., $n < 30$).
4. Prior PI threshold values were established based on evaluating a random sample of aircraft PI values.
5. ACE/AACE PI threshold values are part of the same universal population of PI threshold values.

Depicted in Figure 2-1 are the following nine steps:

Step 1:    Compile historical ACE/AACE PI threshold data.

Step 2:    Summarize data in a form used in conjunction with analysis of variance (ANOVA).

Step 3:    Evaluate PI threshold data to determine treatment and block means, as well as the grand mean.

Step 4:    Determine if one PI threshold value can be established for all aircraft or if individual aircraft PI threshold values should be established.

Step 5:    Calculate a PI threshold value(s).

Step 6:    Determine if calculated PI threshold value(s) is acceptable or not.

Step 7:    Adjust PI threshold value.

Step 8:    Accept adjusted PI threshold value.

Step 9:    Set PI threshold value.

Each of these steps was an integral part of determining the AACE PI threshold values and they are described in the following paragraphs. Their application assures that resulting AACE PI threshold values are rational and defensible from a statistical standpoint.

## Step 1: Compile Historical ACE/AACE PI Threshold Data.

This step involved gathering all pertinent historical ACE/AACE data. Compiled were the ACE PI thresholds set for the applicable aircraft from 1983 to 1986, as well as the profiling data for the individual aircraft which were part of the 1984/1985 major threshold survey. Also, AACE historical data were collected which consisted of the 1986 PI threshold value (i.e., 125) for all aircraft. This AACE PI threshold value was the first ever set and was used for all aircraft since the data collected thus far were determined to be insufficient to make an accurate decision on individual aircraft AACE PI threshold values.

## Step 2: Summarize Data In A Form Used In Conjunction With ANOVA.

This step involved graphically summarizing the data compiled during Step 1. Figure 2-2 presents PI threshold histograms for each of applicable aircraft and illustrates the general normal distribution of PI threshold values for each of the aircraft. The changes in PI threshold values are assumed to be reasonable based on the data that were available. However, it is recognized that changes were often made in concert with indicator adjustments; therefore, it is further assumed that any indicator adjustments made did not significantly alter the potential for a PI threshold value greater than or less than the preceding year.

The data depicted in Figure 2-2 were then formatted into an ANOVA table (see Table 2-1). This table groups the data into four treatments and ten blocks. Treatments were defined to be data per year and blocks were defined to be data per aircraft. The ANOVA table only depicts the ACE historical data; no ANOVA was generated for the AACE data since only one treatment was defined.
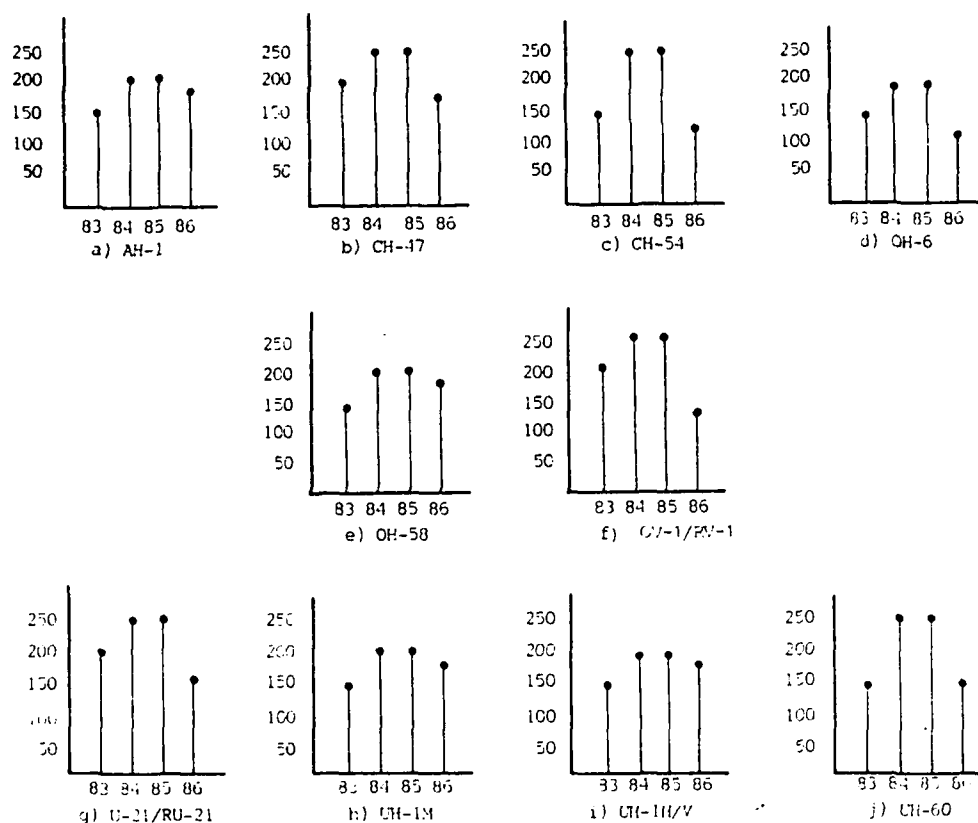
Initiate
Definition
of AACE
PI Calc Threshold
Val. 1987

(1) Compile Historical Act/Acft PI Threshold Data

(2) Summarize Data In A Form Used In Conjunction With ANOVA

(3) Evaluate Data To Determine Threshold PI Means And The Threshold PI Grand Mean

$$\bar{X}_j = \frac{\sum X_{ij}}{r}$$ = PI Mean

$r$ = No. Of Rows

$$\bar{\bar{X}} = \frac{\sum_{i=1}^{r} \sum_{j=1}^{c} X_{ij}}{rc}$$ = Grand Mean

$c$ = No. Of Columns

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\bar{X}_i - \bar{\bar{X}})^2}{n-1}}$$ Standard Deviation

$n$ = No. Of PI Inputs

(4) Option One: Derive Individual Aircraft Thresholds

Option Two: Derive One Threshold PI PI*

(5) Calculate Threshold Using Bayesian Estimation

$$T_1 = \frac{n\bar{T}s_o^2 + T_o s_{\bar{T}}^2}{n s_o^2 + s_{\bar{T}}^2}$$

$n$ = No. Of Data Inputs

$\bar{T}$ (Option 2) = $\bar{x}$

$\bar{T}$ (Option 1) = $\bar{x}$

$s_{\bar{T}}$ (Option 2) = (See Step 3)

$s_{\bar{T}}$ (Option 1) $\sqrt{\frac{\sum_{i=1}^{n}(T_i - \bar{T})^2}{n-1}}$

$T = 1.75$

$s_o = .5$

(6) Determine If AACE Threshold Estimator, $T_1$, Satisfies The Null Hypothesis, $H_o$

$H_o: T_u = T_1$

$H_1: T_u \neq T_1$ (Two-Tailed Test)

$\alpha = 5\%$

$T_u$ = True Threshold

$\alpha = z$ = Type I Error

Decision Is Made Using The Student - t Dist.

$$t = \frac{\bar{T} - T_1}{s_{\bar{T}}/\sqrt{n}}$$

$P\left[t < t_{\alpha/2}\right] = .025$

$P\left[t > t_{\alpha/2}\right] = .025$

$(n-1)$ Degrees Of Freedom

(7) Adjust $T_1$ To PI Value Necessary To Accept $H_o$

Solve: $\pm |t_{\alpha/2}| = \frac{\bar{T} - T_1}{s_{\bar{T}}/\sqrt{n}}$

Reject $H_o$  $-t_{\alpha/2} > t > t_{\alpha/2}$

(8)

Accept $H_o$  $-t_{\alpha/2} < t < t_{\alpha/2}$

(9)

(10) Set AACE Threshold PI To $T_1$

* Note: Performing ANOVA Indicated That Hypothesis That The Historical Threshold PI's Are All From the Same Universal Population, Is Supported. This Test Is Accepted If Student t Calculated Is Less Than Student t Observed.

Figure 2-1  Routine For AACE PI Threshold Value Calculation

Figure 2-2 Aircraft PI Threshold Histogram (PI Threshold vs Year)

Table 2-1 ANOVA Table For ACE Historical Data

| Blocks | Treatments | | | |
|---|---|---|---|---|
| | 1983 | 1984 | 1985 | 1986 |
| AH-1 | 150 | 200 | 200 | 197 |
| CH-47 | 200 | 250 | 250 | 197 |
| CH-54 | 150 | 250 | 250 | 125 |
| OH-6 | 150 | 200 | 200 | 112 |
| OH-58 | 150 | 200 | 200 | 176 |
| OV-1/ RV-1 | 200 | 250 | 250 | 125 |
| U-21/ RU-21 | 200 | 250 | 250 | 128 |
| UH-1M | 150 | 200 | 200 | 156 |
| UH-1 H/V | 150 | 200 | 200 | 161 |
| UH-60 | 150 | 250 | 250 | 150 |

## Step 3: Evaluate PI Threshold Data To Determine Treatment And Block Means, As Well As The Grand Mean

This step involved working with the ANOVA table generated as part of Step 2 to derive key inputs for use in subsequent steps; particularly, to determine if a single AACE PI threshold value for all aircraft would be appropriate. This latter task was performed since the only prior AACE PI threshold value set was a single value (i.e., 125) for all aircraft and it was desired to determine if this precedent should be continued.

Table 2-2 shows the computed treatment and block means, as well as the grand mean. Another value which could have been computed for use in subsequent steps was the standard deviation for the grand mean.

The following equations were used:

$$\text{Block mean, } X_i = \frac{\sum_i X_{ij}}{c}$$

$$\text{Treatment mean, } X_i = \frac{\sum_j X_{ij}}{r}$$

$$\text{Grand mean, } X = \frac{\sum_i \sum_j X_{ij}}{rc}$$

$$\text{Grand Mean standard deviation, } S = \sqrt{\frac{\sum (\bar{X} - \bar{\bar{X}})^2}{n-1}}$$

where:  
$c$ = no. of columns  
$r$ = no. of rows  
$n$ = no. of data points  
$X_{ij}$ = data point in cell $ij$

## Step 4: Determine If One PI Threshold Value Can Be Established For All Aircraft Or If Individual Aircraft PI Threshold Values Should Be Established.

This step involved making a decision to compute either one universal AACE PI threshold value or individual aircraft PI threshold values. To assist in making this decision, ANOVA was performed for the ACE data contained in Table 2-2. This task was deemed necessary for the reasons stated under Step 3.

ANOVA is based on the assumption that there are a variety of contributions to the variations present in a set of data. These variations (variances) can be tested by comparison with estimates of what would normally consist of just simple random errors. The comparison is made using the F-Statistic which is a well-known and tabulated probability density function.

The F-Statistic itself is the ratio of the "between

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## Table 2-2  ANOVA Table For ACE Historical Data

| Blocks | Treatments | | | | |
|---|---|---|---|---|---|
| | 1983 | 1984 | 1985 | 1986 | Block Means |
| Ad-1 | 150 | 200 | 200 | 197 | 187 |
| CH-47 | 200 | 250 | 250 | 197 | 224 |
| CH-54 | 150 | 250 | 250 | 125 | 194 |
| OH-6 | 150 | 200 | 200 | 112 | 166 |
| OH-58 | 150 | 200 | 200 | 176 | 182 |
| OV-1/RV-1 | 200 | 250 | 250 | 125 | 206 |
| J-21/RJ-21 | 200 | 250 | 250 | 128 | 207 |
| UH-1M | 150 | 200 | 200 | 156 | 177 |
| UH-1 H/V | 150 | 200 | 200 | 161 | 178 |
| UH-60 | 150 | 250 | 250 | 150 | 200 |
| Treatment Means | 165 | 225 | 225 | 153 | 192 Grand Mean |

## Table 2-3  ANOVA Calculations

| Source of Variation | Degrees of Freedom | Sum of Square | Mean Square | Ratio of Mean Square (F) |
|---|---|---|---|---|
| Between Blocks (between rows) | r-1 = 9 | | | |
| Between Treatments (between columns) | c-1 = 3 | SST = 44280 | MST = 14760 | MST/MSE = 15.26 |
| Residual (within columns) | (r-1)(c-1) = 27 | SSE = 26107 | MSE = 967 | |
| Total | rc-1 = 39 | | | |

$r = 10$
$c = 4$
$\bar{\bar{x}} = 192$

$$SST = r \sum (\bar{x}_j - \bar{\bar{x}})^2 = 44280$$

$$SSE = \sum_{ji} (x_{ij} - \bar{x}_j)^2 = 26107$$

$$MSE = \frac{SSE}{(r-1)(c-1)} = 967$$

$$MST = \frac{SST}{c-1} = 14760$$

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group" variance to the "error" variance. Since the F-distribution is derived on the assumption that all the data are homogeneous, i.e., that no difference really exists between the groups (generally called the null hypothesis), this ratio should become significantly greater than unity when a difference really exists. A comparison of this calculated ration with the appropriate tabled value for the F-Statistic then allows one to make a probabilistic statement regarding the likelihood that a true difference is present.

Table 2-3 presents the ANOVA computational results. The actual formulae used are presented as part of the table. A null hypothesis was defined to state that all the data are from the same universal population. Also, an alternative hypothesis was defined to state that the data were not all from the same universal population. These hypotheses are as follows:

$$H_o : T_a = T_n$$

$$H_1 : T_a \neq T_n$$

The probability that the computed F value was greater than the tabled value was set at $\alpha = .01$ (i.e., $P \{ F > F_\alpha \} = .01$). Therefore, if the computed F was greater than $F_{.01}$ this would indicate that the null hypothesis cannot be accepted. In comparing the computed F value with $F_{.01}$, the null hypothesis could not be accepted as shown below:

$$F = 15.26 \qquad F_{.01} = 4.60$$

$$F > F_{.01} \text{ therefore, reject } H_o$$

This result corresponded with that expected since the PI threshold means calculated in Table 2-2 were for distinct aircraft types each having a distinct population of PI threshold values. Based on this task it was then decided to calculate individual aircraft PI threshold values (i.e., Option One - see Figure 2-1).

**Step 5: Calculate A PI Threshold Value(s)**

Since Step 4 showed that a single AACE PI threshold value for all aircraft was inappropriate, this step involved calculating value representing the true PI threshold value for each aircraft type. A key assumption, as defined earlier, stated that the ACE/AACE PI threshold data were from the same universal population of thresholds. This assumption was made in recognition of the Army's goal to ultimately define a single ACE/AACE PI threshold value for each aircraft type. Futhermore, it was assumed that the AACE profiling indicators for each aircraft type are similar to and derived from the ACE profiling indicators for each aircraft type. Therefore, both the ACE and AACE indicators provide PI threshold values which

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are related to each other and are part of the same universal population of the PI thresholds.

The task of calculating a value for the true PI threshold for each aircraft type was achieved by using Bayesian statistics. This involves combining a prior value with direct sample evidence. This leads to a posterior distribution of the true PI threshold value which is approximated by a normal distibution using the following formula:

$$\text{True Threshold Estimator, } T_1 = \frac{n \, \bar{T} \, S_o^2 + T_o \, S_{\bar{T}}^2}{n \, S_o^2 + S_{\bar{T}}^2}$$

where,

$n$ = no. of data inputs

$\bar{T}$ = sample data mean

$S_{\bar{T}}$ = sample data variance

$T_o$ = prior true threshold (i.e., 125)

$S_o^2$ = prior variance (i.e., $S^2$=25)

The following are also defined in reference to the data in Table 2-3.

$$\bar{T} \text{ (option 1)} = \bar{X}$$

$$\bar{T} \text{ (option 2)} = \bar{\bar{X}}$$

$$S_{\bar{T}}\text{(option 1)} = \sqrt{\frac{\sum_{i=1}^{n} (T_i - \bar{T})^2}{n - 1}}$$

$$S \text{ (option 2)} = \text{(see Step 3)}$$

The actual AACE PI threshold calculations are presented in Appendix C.

Step 6: **Determine If Calculated PI Threshold Value(s) Is Acceptable Or Not**

This step involved determining if the PI threshold value calculated in Step 5 for each aircraft type could be accepted as representing the true PI threshold value. This was achieved by testing if the mean, T, and standard deviation, $S_T$, of the appropriate sample of PI threshold values from Table 2-2 supported the hypothesis that the calculated representative true PI threshold value was the true PI threshold value. For this test a null hypothesis was established as follows:

$$H_o : T_u = T_1$$

Accordingly, an alternative hypothesis was also established:

$$H_1 : T_u \neq T_1$$

This alternative hypothesis defined the test to be two-tailed. That is, the null hypothesis could not be accepted if $T_u$ was determined to be in either of the shaded areas depicted in Figure 2-3. This test was deemed to be appropriate since it is typically not advantageous to have either underreadiness ($T_u > T_1$, leading to poor combat availability) or overreadiness ($T_u < T_1$, leading to excessive maintenance costs). The defined risk for rejecting the null hypothesis when it is true was 1%. Therefore, each of the shaded areas in Figure 2-3 is $\alpha/2$ or .5%.
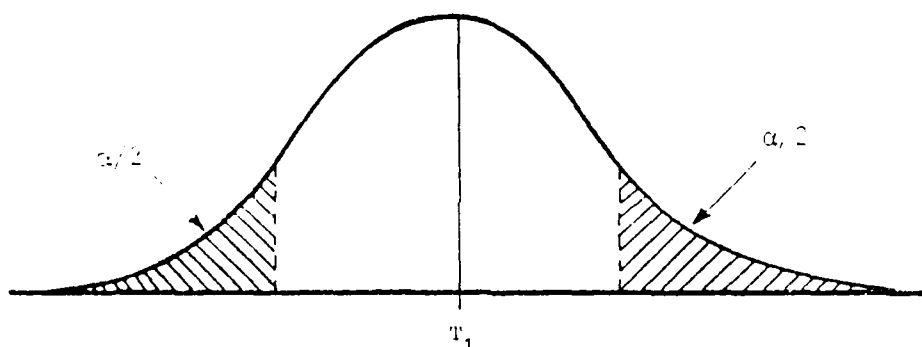


Figure 2-3  Test Distribution

The test statistic used to make the acceptability decision was the Student-t distribution. This distribution was appropriate since the number of data points used in the test was less than thirty. (The student-t distribution approximates the normal distribution for less than thirty data points.) This statistic has the following form:

$$t^* = \frac{\bar{T} - T_1}{S_{\bar{T}} / \sqrt{n}}$$

The critical value, $t^*$, was then compared with the appropriate table value of $t_{\alpha/2}$ (with $n-1$ degrees of freedom) as found in Appendix A. The decision rule was as follows:

reject $H_0$ for $-t_{\alpha/2} > t^* > t_{\alpha/2}$

accept $H_0$ for $-t_{\alpha/2} < t^* < t_{\alpha/2}$

## Step 7: Adjust PI Threshold Value

This step was not applicable but would have involved adjusting any PI threshold values (i.e., value of $T_1$) which were found to be not acceptable during Step 6 to the minimum or maximum value (depending on whether the reject decision was below $-t_{\alpha/2}$ or above $t_{\alpha/2}$) for which an acceptability decision can be made. To determine the adjusted value of $T_1$ the following would have been for $T_1$:

$$\pm \, t_{\alpha/2} = \frac{\bar{T} - T_1}{S_{\bar{T}} \, / \, \sqrt{n}}$$

## Step 8: Accept Adjusted PI Threshold Value

This step was not applicable but would have involved accepting the adjusted PI threshold value from Step 7.

## Step 9: Set PI Threshold Value

This step involved setting the PI threshold for each aircraft type. Its input was the value for $T_1$ which came directly from Step 6. If it had been applicable, the input could have been a value for $T_1$ that was adjusted and accepted through Steps 7 and 8.

## 2.2 Results

The routine described in Subsection 2.1 was applied to determine candidate 1987 AACE PI threshold values for each aircraft type in the ACE/AACE program. Table 2-4 below lists these candidate threshold values, as well as the 1986 threshold values.

Table 2-4  1987 Candidate PI Threshold Values

| Aircraft Type | 1986 PI Threshold Value | 1987 Candidate Threshold Value |
|---|---|---|
| AH-1 | 125 | 134 |
| CH-47 | 125 | 136 |
| CH-54 | 125 | 127 |
| OH-6 | 125 | 127 |
| OH-58 | 125 | 133 |
| OV-1/RV-1 | 125 | 127 |
| U-21/RU-21 | 125 | 127 |
| UH-1M | 125 | 131 |
| UH-1H/V | 125 | 132 |
| UH-60 | 125 | 127 |

The threshold value calculation and acceptability decision for each aircraft type are provided in Appendix C.

## 3.0 DESCRIPTION OF ITEM

The improved threshold evaluation methodology (ITEM) is intended to be applied annually to revise existing ACE or AACE PI threshold values based on the results of profiling or a threshold survey. This routine is similar to that described previously in Subsection 2.1 in that it involves calculating a revised estimate of the true threshold and then testing this estimate for acceptability.

As with the routine described in Subsection 2.1, ITEM is based on several assumptions which are necessary to support the application of the statistical concepts employed. These include the following.

1. There exists a universal population of historical PI threshold values for each aircraft. The mean of this population is the true threshold.
2. The population of PI threshold values for each aircraft is normally distributed.
3. The Student-t distribution approximates the normal distribution for small sample sizes (i.e., $n < 30$).
4. Prior PI threshold values were established based on evaluating a random sample of aircraft PI values.
5. ACE/AACE PI threshold values are part of the same universal population of PI threshold values.

Depicted in Figure 3-1 are the following nine steps:
Step 1: Define Parameter Notation.
Step 2: Determine Number Of Aircraft Or PIs To Look At.
Step 3: Identify PIs Within Confidence Interval From Profiling Data Or Depot Candidates From Survey Data.
Step 4: Calculate Mean And Variance Of Appropriate Data.
Step 5: Calculate A PI Threshold Value.
Step 6: Determine If Calculated PI Threshold Value Is Acceptable Or Not.
Step 7: Adjust PI Threshold Value.
Step 8: Accept Adjusted PI Threshold Value.
Step 9: Set PI Threshold Value.

Each of these steps is an integral part of ITEM and they are described in the following paragraphs. Their application provide assurance that resulting ACE or AACE PI threshold values are rational and defensible from a statistical standpoint.

### Step 1: Define Parameter Notation

This step involves defining parameter notation for use in subsequent routine steps. The preceding year's PI threshold for a specific aircraft type is set equal to $T_o$. If the preceding year's PI threshold was set using this routine, then $T_1$ is set equal to $T_o$. Likewise the preceding year's PI threshold standard deviation, $S_1$, is set to $S_o$.

### Step 2: Determine Number of Aircraft Or PIs To Look At

This step involves determining how many aircraft should be evaluated as part of a PI threshold survey or the range of aircraft PIs from the profiling data which should be further evaluated. The latter will in turn define a

Figure 3-1   Improved Threshold Evaluation Methodology (1tem)

number of aircraft PIs which is necessary for subsequent routine steps. Both of these options are based on a defined maximum amount of acceptable error, E, between the true PI threshold, $T_u$, and its estimator. As shown in Figure 3-2, the distribution of data to be evaluated is assumed to be normal.
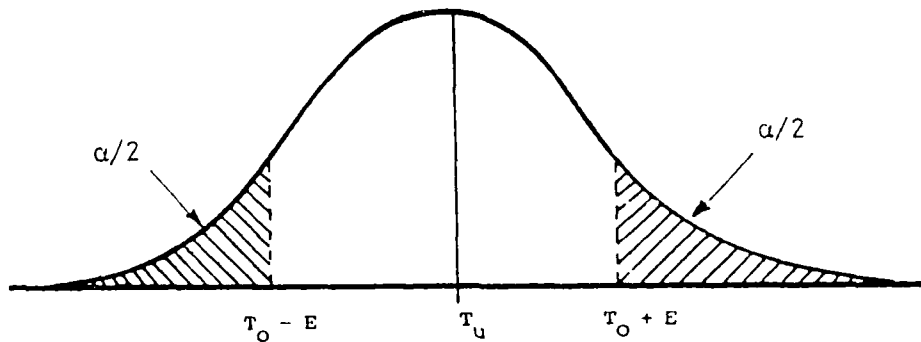


Figure 3-2  Distribution of Data

The quantity of data to be looked at is contained within a 99% confidence interval about $T_u$. This interval is defined as follows:

$$T_o - E < T_u < T_o + E$$

The error term is defined by:

$$E = Z_{\alpha/2} \frac{S_o}{\sqrt{n}}$$

where:

$Z_{\alpha/2}$ = the normal deviate for the area of the confidence interval under the normal curve (=2.575)

$S_o$ = PI threshold value standard deviation

$n$ = minimum quantity of data points within the confidence interval

Solving this equation for n

$$n = \left[ \frac{Z_{\alpha/2} \, S_o}{E} \right]^2$$

and defining E to be 5 PI points, the number of aircraft which should be addressed as part of a PI threshold survey is determined. Also, by setting E

equal to 5 PI points the range of PIs within the annual profiling data to be addressed is determined.

This step is intended to focus engineering attention only on those aircraft which have a PI about an expected PI threshold value. Likewise, it is intended to identify a range of profiling PI data about an expected PI threshold value. For either option, there may be aircraft with PI values beyond the lower or upper end of the confidence interval (see Figure 3-2) that are indeed depot candidates; however, these are part of the defined risk. The region of PI values defined by the confidence interval forces the most reasonable PI threshold value to be set in subsequent routine steps.

## Step 3: Identify PIs within Confidence Interval from Profiling Data or Depot Candidates from Survey Data

This step involves using the information defined by Step 2 depending on whether it is desired to revise the AACE PI threshold value based on PI threshold survey data or profiling data. It should be noted that an inherent part of Step 3 is to perform the PI threshold survey or aircraft profiling as the selected option dictates. For Option 1 (i.e. identify PIs from profiling data within confidence interval), the number and values of PIs falling within the appropriately defined interval are recorded for use with Step 4. For Option 2 (i.e., identify depot candidates from survey data), the number of aircraft defined as depot candidates (and their values) within the Step 2 defined survey size are recorded for use with Step 4.

## Step 4: Calculate Mean and Variance of Appropriate Data

This step involves calculating the mean and standard deviation of the data recorded as part of Step 3. The formulae to perform the calculations are as follows:

$$\text{Mean,} \quad \bar{T} = \frac{\sum_{i=1}^{K} T_i}{K}$$

$$\text{Variance,} \quad S_{\bar{T}}^2 = \frac{\sum_{i=1}^{K} (T_i - \bar{T})^2}{K - 1}$$

where for Option 1:

$K$ = number of PIs within defined confidence internal

$T_i$ = PI value

and for Option 2:

$K$ = number of aircraft identified as depot candidates

$T_i$ = PI value

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**Step 5: Calculate a PI Threshold Value**

This step involves calculating a value representing the true PI threshold for a specific aircraft type. This value is calculated using Bayesian statistics and requires combining prior information (i.e., the preceding year input data: $T_1$ and $S_1$ we·e set to $T_\sigma$ and $S_o$ respectively in Step 1) with the current year's direct sample evidence calculated in Step 4. This leads to a posterior distribution of the time PI threshold value which is approximated by a normal distribution using the following formulae:

$$\text{True Threshold, } T_1 = \frac{K \bar{T} S_o + T_o S_{\bar{T}}^2}{K S_o^2 + S_{\bar{T}}^2}$$

$$\text{Distribution Variance, } S_1^2 = \frac{S_{\bar{T}}^2 S_o}{K S_o^2 + S_{\bar{T}}^2}$$

where:

$K$ = number of data inputs
$\bar{T}_2$ = sample data mean
$S_{\bar{T}}$ = sample data variance
$T_o$ = prior representative true threshold
$S_o^2$ = prior representative distribution variance

**Step 6: Determine if Calculated PI Threshold is Acceptable or Not**

This step involves determining if the PI threshold value calculated in Step 5, as representing the true PI threshold value, can be accepted as the PI threshold value for the current year. This is achieved by testing if the current year's PI sample evidence (i.e. mean and standard deviation) supports the hypothesis that the calculated representative for the true PI threshold value is the PI threshold value.

For this test, a null hypothesis is established as follows:

$$H_o : T_u = T_1$$

Accordingly, an alternative hypothesis is also established:

$$H_1 : T_u \neq T_1$$

This alternative hypothesis defines the test to be two-tailed. That is, the null hypothesis cannot be accepted if $T_u$ is determined to be in either of the shaded areas depicted in Figure 3-3. This test is deemed to be appropriate since it is typically not advantageous to have either under readiness ($T_u <$ $T_1$, leading to poor combat availability) or overreadiness ($T_u > T_1$, leading to excessive maintenance costs). The defined risk for rejecting the null hypothesis when it is true is 5%. Therefore, each of the shaded areas in Figure 3-3 is $\alpha/2$ or 2.5%.
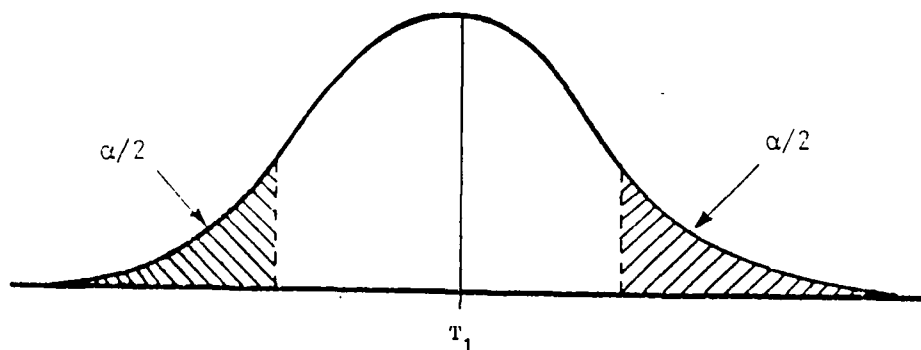
Figure 3-3 Test Distribution

Depending on the size of the sample evidence, the acceptability decision is either based on the normal distribution (i.e., $n \geq 30$) or the Student-t distribution (i.e., $n < 30$). (Note that the Student-t distribution estimates the normal distribution for small sample sizes).

The test statistics are as follows:

$$\text{Normal, } z^* = \frac{\bar{T} - T_1}{S_{\bar{T}} / \sqrt{n}}$$

$$\text{Student-t, } t^* = \frac{\bar{T} - T_1}{S_{\bar{T}} / \sqrt{n}}$$

The critical value, $z^*$ or $t^*$, is then compared with the appropriate tabled value of $z_{\alpha/2}$ or $t_{\alpha/2}$ (with n-1 degrees of freedom) as found in Appendix A. The decision rule is as follows:

reject H for: $-z_{\alpha/2} > z^* > z_{\alpha/2}$ or

$$-t_{\alpha/2} > t^* > t_{\alpha/2}$$

accept H for: $-z_{\alpha/2} < z^* < z_{\alpha/2}$ or

$$-t_{\alpha/2} < t^* < t_{\alpha/2}$$

## Step 7: Adjust PI Threshold Value

This step involves adjusting a PI threshold value (i.e., value of $T_1$) found to be not acceptable during Step 6 to the minimum or maximum value (depending on whether the $z^*$ or $t^*$ was below $-z_{\alpha/2}$ or $-t_{\alpha/2}$ or above $z_{\alpha/2}$ or $t_{\alpha/2}$) for which an accept decision can be made. To determine the adjusted value of $T_1$, the following appropriate formula is solved for $T_1$:

$$\pm z_{\alpha/2} = \frac{\bar{T} - T_1}{S_{\bar{T}} / \sqrt{n}}$$

$$\pm t_{\alpha/2} = \frac{\bar{T} - T_1}{S_{\bar{T}} / \sqrt{n}}$$

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**Step 8: Accept Adjusted PI Threshold Value**

This step involves accepting (see Step 6) the adjusted PI threshold value from Step 7.

**Step 9: Set PI Threshold Value**

This step involves setting the PI threshold for each aircraft type. Its input is the value for $T_l$ which either comes directly from Step 6 or is adjusted and accepted through Steps 7 and 8.

## 4.0 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to derive improved AACE PI threshold values for 1987. The study achieved its objective by establishing candidate PI threshold values for the AH-1, CH-47, CH-54, OH-6, OH-58, OV-1/RV-1, U-21/RU-21, UH-1M, UH-1H/V, and UH-60 aircraft. In addition, an improved threshold evaluation methodology (ITEM) was defined during the study. ITEM provides a statistically-based, rational means for defining engineering ACE or AACE PI threshold values. It is designed for annual application to update the PI threshold value for each aircraft type participating in the ACE/AACE program.

Based on the results of this study, the following tasks are recommended:
1. Apply ITEM annually to update ACE and AACE PI threshold values.
2. Incorporate a detailed description of ITEM into the AACE/AACE Inspection and Analysis Handbook.
3. Automate ITEM for ease of use and complete data storage.

APPENDIX A
STATISTICAL TABLES

## Normal Distribution Function

$$F(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-(1/2)t^2}\, dt$$

| z | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|------|------|------|------|------|------|------|------|------|------|
| 0.0 | 0.5000 | 0.5040 | 0.5080 | 0.5120 | 0.5160 | 0.5199 | 0.5239 | 0.5279 | 0.5319 | 0.5359 |
| 0.1 | 0.5398 | 0.5438 | 0.5478 | 0.5517 | 0.5557 | 0.5596 | 0.5636 | 0.5675 | 0.5714 | 0.5753 |
| 0.2 | 0.5793 | 0.5832 | 0.5871 | 0.5910 | 0.5948 | 0.5987 | 0.6026 | 0.6064 | 0.6103 | 0.6141 |
| 0.3 | 0.6179 | 0.6217 | 0.6255 | 0.6293 | 0.6331 | 0.6368 | 0.6406 | 0.6443 | 0.6480 | 0.6517 |
| 0.4 | 0.6554 | 0.6591 | 0.6628 | 0.6664 | 0.6700 | 0.6736 | 0.6772 | 0.6808 | 0.6844 | 0.6879 |
| 0.5 | 0.6915 | 0.6950 | 0.6985 | 0.7019 | 0.7054 | 0.7088 | 0.7123 | 0.7157 | 0.7190 | 0.7224 |
| 0.6 | 0.7257 | 0.7291 | 0.7324 | 0.7357 | 0.7389 | 0.7422 | 0.7454 | 0.7486 | 0.7517 | 0.7549 |
| 0.7 | 0.7580 | 0.7611 | 0.7642 | 0.7673 | 0.7704 | 0.7734 | 0.7764 | 0.7794 | 0.7823 | 0.7852 |
| 0.8 | 0.7881 | 0.7910 | 0.7939 | 0.7967 | 0.7995 | 0.8023 | 0.8051 | 0.8078 | 0.8106 | 0.8133 |
| 0.9 | 0.8159 | 0.8186 | 0.8212 | 0.8238 | 0.8264 | 0.8289 | 0.8315 | 0.8340 | 0.8365 | 0.8389 |
| 1.0 | 0.8413 | 0.8438 | 0.8461 | 0.8485 | 0.8508 | 0.8531 | 0.8554 | 0.8577 | 0.8599 | 0.8621 |
| 1.1 | 0.8643 | 0.8665 | 0.8686 | 0.8708 | 0.8729 | 0.8749 | 0.8770 | 0.8790 | 0.8810 | 0.8830 |
| 1.2 | 0.8849 | 0.8869 | 0.8888 | 0.8907 | 0.8925 | 0.8944 | 0.8962 | 0.8980 | 0.8997 | 0.9015 |
| 1.3 | 0.9032 | 0.9049 | 0.9066 | 0.9082 | 0.9099 | 0.9115 | 0.9131 | 0.9147 | 0.9162 | 0.9177 |
| 1.4 | 0.9192 | 0.9207 | 0.9222 | 0.9236 | 0.9251 | 0.9265 | 0.9279 | 0.9292 | 0.9306 | 0.9319 |
| 1.5 | 0.9332 | 0.9345 | 0.9357 | 0.9370 | 0.9382 | 0.9394 | 0.9406 | 0.9418 | 0.9429 | 0.9441 |
| 1.6 | 0.9452 | 0.9463 | 0.9474 | 0.9484 | 0.9495 | 0.9505 | 0.9515 | 0.9525 | 0.9535 | 0.9545 |
| 1.7 | 0.9554 | 0.9564 | 0.9573 | 0.9582 | 0.9591 | 0.9599 | 0.9608 | 0.9616 | 0.9625 | 0.9633 |
| 1.8 | 0.9641 | 0.9649 | 0.9656 | 0.9664 | 0.9671 | 0.9678 | 0.9686 | 0.9693 | 0.9699 | 0.9706 |
| 1.9 | 0.9713 | 0.9719 | 0.9726 | 0.9732 | 0.9738 | 0.9744 | 0.9750 | 0.9756 | 0.9761 | 0.9767 |
| 2.0 | 0.9772 | 0.9778 | 0.9783 | 0.9788 | 0.9793 | 0.9798 | 0.9803 | 0.9808 | 0.9812 | 0.9817 |
| 2.1 | 0.9821 | 0.9826 | 0.9830 | 0.9834 | 0.9838 | 0.9842 | 0.9846 | 0.9850 | 0.9854 | 0.9857 |
| 2.2 | 0.9861 | 0.9864 | 0.9868 | 0.9871 | 0.9875 | 0.9878 | 0.9881 | 0.9884 | 0.9887 | 0.9890 |
| 2.3 | 0.9893 | 0.9896 | 0.9898 | 0.9901 | 0.9904 | 0.9906 | 0.9909 | 0.9911 | 0.9913 | 0.9916 |
| 2.4 | 0.9918 | 0.9920 | 0.9922 | 0.9925 | 0.9927 | 0.9929 | 0.9931 | 0.9932 | 0.9934 | 0.9936 |
| 2.5 | 0.9938 | 0.9940 | 0.9941 | 0.9943 | 0.9945 | 0.9946 | 0.9948 | 0.9949 | 0.9951 | 0.9952 |
| 2.6 | 0.9953 | 0.9955 | 0.9956 | 0.9957 | 0.9959 | 0.9960 | 0.9961 | 0.9962 | 0.9963 | 0.9964 |
| 2.7 | 0.9965 | 0.9966 | 0.9967 | 0.9968 | 0.9969 | 0.9970 | 0.9971 | 0.9972 | 0.9973 | 0.9974 |
| 2.8 | 0.9974 | 0.9975 | 0.9976 | 0.9977 | 0.9977 | 0.9978 | 0.9979 | 0.9979 | 0.9980 | 0.9981 |
| 2.9 | 0.9981 | 0.9982 | 0.9982 | 0.9983 | 0.9984 | 0.9984 | 0.9985 | 0.9985 | 0.9986 | 0.9986 |
| 3.0 | 0.9987 | 0.9987 | 0.9987 | 0.9988 | 0.9988 | 0.9989 | 0.9989 | 0.9989 | 0.9990 | 0.9990 |
| 3.1 | 0.9990 | 0.9991 | 0.9991 | 0.9991 | 0.9992 | 0.9992 | 0.9992 | 0.9992 | 0.9993 | 0.9993 |
| 3.2 | 0.9993 | 0.9993 | 0.9994 | 0.9994 | 0.9994 | 0.9994 | 0.9994 | 0.9995 | 0.9995 | 0.9995 |
| 3.3 | 0.9995 | 0.9995 | 0.9995 | 0.9996 | 0.9996 | 0.9996 | 0.9996 | 0.9996 | 0.9996 | 0.9997 |
| 3.4 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9998 |
| 3.5 | 0.9998 | | | | | | | | | |
| 4.0 | 0.99997 | | | | | | | | | |
| 5.0 | 0.9999997 | | | | | | | | | |
| 6.0 | 0.999999999 | | | | | | | | | |

## Values of $t_\alpha$*

| $\nu$ | $\alpha = 0.10$ | $\alpha = 0.05$ | $\alpha = 0.025$ | $\alpha = 0.01$ | $\alpha = 0.005$ | $\nu$ |
|-------|------|------|------|------|------|-------|
| 1 | 3.078 | 6.314 | 12.706 | 31.821 | 63.657 | 1 |
| 2 | 1.886 | 2.920 | 4.303 | 6.965 | 9.925 | 2 |
| 3 | 1.638 | 2.353 | 3.182 | 4.541 | 5.841 | 3 |
| 4 | 1.533 | 2.132 | 2.776 | 3.747 | 4.604 | 4 |
| 5 | 1.476 | 2.015 | 2.571 | 3.365 | 4.032 | 5 |
| 6 | 1.440 | 1.943 | 2.447 | 3.143 | 3.707 | 6 |
| 7 | 1.415 | 1.895 | 2.365 | 2.998 | 3.499 | 7 |
| 8 | 1.397 | 1.860 | 2.306 | 2.896 | 3.355 | 8 |
| 9 | 1.383 | 1.833 | 2.262 | 2.821 | 3.250 | 9 |
| 10 | 1.372 | 1.812 | 2.228 | 2.764 | 3.169 | 10 |
| 11 | 1.363 | 1.796 | 2.201 | 2.718 | 3.106 | 11 |
| 12 | 1.356 | 1.782 | 2.179 | 2.681 | 3.055 | 12 |
| 13 | 1.350 | 1.771 | 2.160 | 2.650 | 3.012 | 13 |
| 14 | 1.345 | 1.761 | 2.145 | 2.624 | 2.977 | 14 |
| 15 | 1.341 | 1.753 | 2.131 | 2.602 | 2.947 | 15 |
| 16 | 1.337 | 1.746 | 2.120 | 2.583 | 2.921 | 16 |
| 17 | 1.333 | 1.740 | 2.110 | 2.567 | 2.898 | 17 |
| 18 | 1.330 | 1.734 | 2.101 | 2.552 | 2.878 | 18 |
| 19 | 1.328 | 1.729 | 2.093 | 2.539 | 2.861 | 19 |
| 20 | 1.325 | 1.725 | 2.086 | 2.528 | 2.845 | 20 |
| 21 | 1.323 | 1.721 | 2.080 | 2.518 | 2.831 | 21 |
| 22 | 1.321 | 1.717 | 2.074 | 2.508 | 2.819 | 22 |
| 23 | 1.319 | 1.714 | 2.069 | 2.500 | 2.807 | 23 |
| 24 | 1.318 | 1.711 | 2.064 | 2.492 | 2.797 | 24 |
| 25 | 1.316 | 1.708 | 2.060 | 2.485 | 2.787 | 25 |
| 26 | 1.315 | 1.706 | 2.056 | 2.479 | 2.779 | 26 |
| 27 | 1.314 | 1.703 | 2.052 | 2.473 | 2.771 | 27 |
| 28 | 1.313 | 1.701 | 2.048 | 2.467 | 2.763 | 28 |
| 29 | 1.311 | 1.699 | 2.045 | 2.462 | 2.756 | 29 |
| inf | 1.282 | 1.645 | 1.960 | 2.326 | 2.576 | inf |

## Values of $F_{0.01}$ [*]

$\nu_1$ = Degrees of freedom for numerator

| $\nu_2$ = Degrees of freedom for denominator | ... | 8 | 9 | 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 5,982 | 6,023 | 6,056 | 6,106 | 6,157 | 6,209 | 6,235 | 6,261 | 6,287 | 6,313 | 6,339 | 6,366 |
| 2 | | 99.40 | 99.40 | 99.40 | 99.40 | 99.40 | 99.40 | 99.50 | 99.50 | 99.50 | 99.50 | 99.50 | 99.50 |
| 3 | | 27.50 | 27.30 | 27.20 | 27.10 | 26.90 | 26.70 | 26.60 | 26.50 | 26.40 | 26.30 | 26.20 | 26.10 |
| 4 | | 14.80 | 14.70 | 14.50 | 14.40 | 14.20 | 14.00 | 13.90 | 13.80 | 13.70 | 13.70 | 13.60 | 13.50 |
| 5 | | 10.30 | 10.20 | 10.10 | 9.89 | 9.72 | 9.55 | 9.47 | 9.38 | 9.29 | 9.20 | 9.11 | 9.02 |
| 6 | | 8.10 | 7.98 | 7.87 | 7.72 | 7.56 | 7.40 | 7.31 | 7.23 | 7.14 | 7.06 | 6.97 | 6.88 |
| 7 | | 6.84 | 6.72 | 6.62 | 6.47 | 6.31 | 6.16 | 6.07 | 5.99 | 5.91 | 5.82 | 5.74 | 5.65 |
| 8 | | 6.03 | 5.91 | 5.81 | 5.67 | 5.52 | 5.36 | 5.28 | 5.20 | 5.12 | 5.03 | 4.95 | 4.83 |
| 9 | | 5.47 | 5.35 | 5.26 | 5.11 | 4.96 | 4.81 | 4.73 | 4.65 | 4.57 | 4.48 | 4.40 | 4.31 |
| 10 | | 5.06 | 4.94 | 4.85 | 4.71 | 4.56 | 4.41 | 4.33 | 4.25 | 4.17 | 4.08 | 4.00 | 3.91 |
| 11 | | 4.74 | 4.63 | 4.54 | 4.40 | 4.25 | 4.10 | 4.02 | 3.94 | 3.86 | 3.78 | 3.69 | 3.60 |
| 12 | | 4.50 | 4.39 | 4.30 | 4.16 | 4.01 | 3.86 | 3.78 | 3.70 | 3.62 | 3.54 | 3.45 | 3.36 |
| 13 | | 4.30 | 4.19 | 4.10 | 3.96 | 3.82 | 3.66 | 3.59 | 3.51 | 3.43 | 3.34 | 3.25 | 3.17 |
| 14 | | 4.14 | 4.03 | 3.94 | 3.80 | 3.66 | 3.51 | 3.43 | 3.35 | 3.27 | 3.18 | 3.09 | 3.00 |
| 15 | | 4.00 | 3.89 | 3.80 | 3.67 | 3.52 | 3.37 | 3.29 | 3.21 | 3.13 | 3.05 | 2.96 | 2.87 |
| 16 | | 3.89 | 3.78 | 3.69 | 3.55 | 3.41 | 3.26 | 3.18 | 3.10 | 3.02 | 2.93 | 2.84 | 2.75 |
| 17 | | 3.79 | 3.68 | 3.59 | 3.46 | 3.31 | 3.16 | 3.08 | 3.00 | 2.92 | 2.83 | 2.75 | 2.65 |
| 18 | | 3.71 | 3.60 | 3.51 | 3.37 | 3.23 | 3.08 | 3.00 | 2.92 | 2.84 | 2.75 | 2.66 | 2.57 |
| 19 | | 3.63 | 3.52 | 3.43 | 3.30 | 3.15 | 3.00 | 2.92 | 2.84 | 2.76 | 2.67 | 2.58 | 2.49 |
| 20 | | 3.56 | 3.46 | 3.37 | 3.23 | 3.09 | 2.94 | 2.86 | 2.78 | 2.69 | 2.61 | 2.52 | 2.42 |
| 21 | | 3.51 | 3.40 | 3.31 | 3.17 | 3.03 | 2.88 | 2.80 | 2.72 | 2.64 | 2.55 | 2.46 | 2.36 |
| 22 | | 3.45 | 3.35 | 3.26 | 3.12 | 2.98 | 2.83 | 2.75 | 2.67 | 2.58 | 2.50 | 2.40 | 2.31 |
| 24 | | 3.36 | 3.26 | 3.17 | 3.03 | 2.89 | 2.74 | 2.66 | 2.58 | 2.49 | 2.40 | 2.31 | 2.21 |
| 26 | | | | | | | | | | | | | 2.17 |
| 30 | | 3.17 | 3.07 | 2.98 | 2.84 | 2.70 | 2.55 | 2.47 | 2.39 | 2.30 | 2.21 | 2.11 | 2.01 |
| 40 | | 2.99 | 2.89 | 2.80 | 2.66 | 2.52 | 2.37 | 2.29 | 2.20 | 2.11 | 2.02 | 1.92 | 1.80 |
| 60 | | 2.82 | 2.72 | 2.63 | 2.50 | 2.35 | 2.20 | 2.12 | 2.03 | 1.94 | 1.84 | 1.73 | 1.60 |
| 120 | | 2.66 | 2.56 | 2.47 | 2.34 | 2.19 | 2.03 | 1.95 | 1.86 | 1.76 | 1.66 | 1.53 | 1.38 |
| ∞ | | 2.51 | 2.41 | 2.32 | 2.18 | 2.04 | 1.88 | 1.79 | 1.70 | 1.59 | 1.47 | 1.32 | 1.00 |

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## Values of $F_{0.05}$*

$\nu_1$ = Degrees of freedom for numerator

$\nu_2$ = Degrees of freedom for denominator

| $\nu_2$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12 | 15 | 20 | 24 | 30 | 40 | 60 | 120 | ∞ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 161 | 200 | 216 | 225 | 230 | 234 | 237 | 239 | 241 | 242 | 244 | 246 | 248 | 249 | 250 | 251 | 252 | 253 | 254 |
| 2 | 18.51 | 19.00 | 19.16 | 19.25 | 19.30 | 19.33 | 19.35 | 19.37 | 19.38 | 19.40 | 19.41 | 19.43 | 19.45 | 19.45 | 19.46 | 19.47 | 19.48 | 19.49 | 19.50 |
| 3 | 10.13 | 9.55 | 9.28 | 9.12 | 9.01 | 8.94 | 8.89 | 8.85 | 8.81 | 8.79 | 8.74 | 8.70 | 8.66 | 8.64 | 8.62 | 8.59 | 8.57 | 8.55 | 8.53 |
| 4 | 7.71 | 6.94 | 6.59 | 6.39 | 6.26 | 6.16 | 6.09 | 6.04 | 6.00 | 5.96 | 5.91 | 5.86 | 5.80 | 5.77 | 5.75 | 5.72 | 5.69 | 5.66 | 5.63 |
| 5 | 6.61 | 5.79 | 5.41 | 5.19 | 5.05 | 4.95 | 4.88 | 4.82 | 4.77 | 4.74 | 4.68 | 4.62 | 4.56 | 4.53 | 4.50 | 4.46 | 4.43 | 4.40 | 4.37 |
| 6 | 5.99 | 5.14 | 4.76 | 4.53 | 4.39 | 4.28 | 4.21 | 4.15 | 4.10 | 4.06 | 4.00 | 3.94 | 3.87 | 3.84 | 3.81 | 3.77 | 3.74 | 3.70 | 3.67 |
| 7 | 5.59 | 4.74 | 4.35 | 4.12 | 3.97 | 3.87 | 3.79 | 3.73 | 3.68 | 3.64 | 3.57 | 3.51 | 3.44 | 3.41 | 3.38 | 3.34 | 3.30 | 3.27 | 3.23 |
| 8 | 5.32 | 4.46 | 4.07 | 3.84 | 3.69 | 3.58 | 3.50 | 3.44 | 3.39 | 3.35 | 3.28 | 3.22 | 3.15 | 3.12 | 3.08 | 3.04 | 3.01 | 2.97 | 2.93 |
| 9 | 5.12 | 4.26 | 3.86 | 3.63 | 3.48 | 3.37 | 3.29 | 3.23 | 3.18 | 3.14 | 3.07 | 3.01 | 2.94 | 2.90 | 2.86 | 2.83 | 2.79 | 2.75 | 2.71 |
| 10 | 4.96 | 4.10 | 3.71 | 3.48 | 3.33 | 3.22 | 3.14 | 3.07 | 3.02 | 2.98 | 2.91 | 2.85 | 2.77 | 2.74 | 2.70 | 2.66 | 2.62 | 2.58 | 2.54 |
| 11 | 4.84 | 3.98 | 3.59 | 3.36 | 3.20 | 3.09 | 3.01 | 2.95 | 2.90 | 2.85 | 2.79 | 2.72 | 2.65 | 2.61 | 2.57 | 2.53 | 2.49 | 2.45 | 2.40 |
| 12 | 4.75 | 3.89 | 3.49 | 3.26 | 3.11 | 3.00 | 2.91 | 2.85 | 2.80 | 2.75 | 2.69 | 2.62 | 2.54 | 2.51 | 2.47 | 2.43 | 2.38 | 2.34 | 2.30 |
| 13 | 4.67 | 3.81 | 3.41 | 3.18 | 3.03 | 2.92 | 2.83 | 2.77 | 2.71 | 2.67 | 2.60 | 2.53 | 2.46 | 2.42 | 2.38 | 2.34 | 2.30 | 2.25 | 2.21 |
| 14 | 4.60 | 3.74 | 3.34 | 3.11 | 2.96 | 2.85 | 2.76 | 2.70 | 2.65 | 2.60 | 2.53 | 2.46 | 2.39 | 2.35 | 2.31 | 2.27 | 2.22 | 2.18 | 2.13 |
| 15 | 4.54 | 3.68 | 3.29 | 3.06 | 2.90 | 2.79 | 2.71 | 2.64 | 2.59 | 2.54 | 2.48 | 2.40 | 2.33 | 2.29 | 2.25 | 2.20 | 2.16 | 2.11 | 2.07 |
| 16 | 4.49 | 3.63 | 3.24 | 3.01 | 2.85 | 2.74 | 2.66 | 2.59 | 2.54 | 2.49 | 2.42 | 2.35 | 2.28 | 2.24 | 2.19 | 2.15 | 2.11 | 2.06 | 2.01 |
| 17 | 4.45 | 3.59 | 3.20 | 2.96 | 2.81 | 2.70 | 2.61 | 2.55 | 2.49 | 2.45 | 2.38 | 2.31 | 2.23 | 2.19 | 2.15 | 2.10 | 2.06 | 2.01 | 1.96 |
| 18 | 4.41 | 3.55 | 3.16 | 2.93 | 2.77 | 2.66 | 2.58 | 2.51 | 2.46 | 2.41 | 2.34 | 2.27 | 2.19 | 2.15 | 2.11 | 2.06 | 2.02 | 1.97 | 1.93 |
| 19 | 4.38 | 3.52 | 3.13 | 2.90 | 2.74 | 2.63 | 2.54 | 2.48 | 2.42 | 2.38 | 2.31 | 2.23 | 2.16 | 2.11 | 2.07 | 2.03 | 1.98 | 1.93 | 1.88 |
| 20 | 4.35 | 3.49 | 3.10 | 2.87 | 2.71 | 2.60 | 2.51 | 2.45 | 2.39 | 2.35 | 2.28 | 2.20 | 2.12 | 2.08 | 2.04 | 1.99 | 1.95 | 1.90 | 1.84 |
| 21 | 4.32 | 3.47 | 3.07 | 2.84 | 2.68 | 2.57 | 2.49 | 2.42 | 2.37 | 2.32 | 2.25 | 2.18 | 2.10 | 2.05 | 2.01 | 1.96 | 1.92 | 1.87 | 1.81 |
| 22 | 4.30 | 3.44 | 3.05 | 2.82 | 2.66 | 2.55 | 2.46 | 2.40 | 2.34 | 2.30 | 2.23 | 2.15 | 2.07 | 2.03 | 1.98 | 1.94 | 1.89 | 1.84 | 1.78 |
| 23 | 4.28 | 3.42 | 3.03 | 2.80 | 2.64 | 2.53 | 2.44 | 2.37 | 2.32 | 2.27 | 2.20 | 2.13 | 2.05 | 2.01 | 1.96 | 1.91 | 1.86 | 1.81 | 1.76 |
| 24 | 4.26 | 3.40 | 3.01 | 2.78 | 2.62 | 2.51 | 2.42 | 2.36 | 2.30 | 2.25 | 2.18 | 2.11 | 2.03 | 1.98 | 1.94 | 1.89 | 1.84 | 1.79 | 1.73 |
| 25 | 4.24 | 3.39 | 2.99 | 2.76 | 2.60 | 2.49 | 2.40 | 2.34 | 2.28 | 2.24 | 2.16 | 2.09 | 2.01 | 1.96 | 1.92 | 1.87 | 1.82 | 1.77 | 1.71 |
| 30 | 4.17 | 3.32 | 2.92 | 2.69 | 2.53 | 2.42 | 2.33 | 2.27 | 2.21 | 2.16 | 2.09 | 2.01 | 1.93 | 1.89 | 1.84 | 1.79 | 1.74 | 1.68 | 1.62 |
| 40 | 4.08 | 3.23 | 2.84 | 2.61 | 2.45 | 2.34 | 2.25 | 2.18 | 2.12 | 2.08 | 2.00 | 1.92 | 1.84 | 1.79 | 1.74 | 1.69 | 1.64 | 1.58 | 1.51 |
| 60 | 4.00 | 3.15 | 2.76 | 2.53 | 2.37 | 2.25 | 2.17 | 2.10 | 2.04 | 1.99 | 1.92 | 1.84 | 1.75 | 1.70 | 1.65 | 1.59 | 1.53 | 1.47 | 1.39 |
| 120 | 3.92 | 3.07 | 2.68 | 2.45 | 2.29 | 2.17 | 2.09 | 2.02 | 1.96 | 1.91 | 1.83 | 1.75 | 1.66 | 1.61 | 1.55 | 1.50 | 1.43 | 1.35 | 1.25 |
| ∞ | 3.84 | 3.00 | 2.60 | 2.37 | 2.21 | 2.10 | 2.01 | 1.94 | 1.88 | 1.83 | 1.75 | 1.67 | 1.57 | 1.52 | 1.46 | 1.39 | 1.32 | 1.22 | 1.00 |

## APPENDIX B
## REFERENCES

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APPENDIX C
1987 AACE CANDIDATE
PI THRESHOLD VALUE
CALCULATIONS

# AH-1   AACE Calculation

$n \quad = 4$

$T_o \ = 125$

$s_o \ = 5$

$T \quad = 224$

$s_T \ = 24.5$

$$T_1 = \frac{(4)(187)(25) + (125)(625)}{(4)(25) + (625)}$$

$$T_1 = \frac{96825}{725} = 134$$

$H_o : \ T_u = T_1$

$H_1 : \ T_u \neq T_1$

reject $H_o$ for $t^* > \mid t_{\alpha/2} \mid$        $t_{.005,3} = 5.841$

$$\frac{187 - 134}{25/\sqrt{4}} = \frac{53}{12.5} = 4.24$$

$t^* \not> \mid t_{\alpha/2} \mid \therefore$ cannot reject $H_o$

AACE PI Threshold Value is set at 134

# CH–47 AACE Threshold Calculation

$n = 4$

$T_O = 125$    $T_1 = \dfrac{(4)(224)(25)+(125)(900)}{(4)(25) + 900}$

$S_O = 5$

$T = 224$    $= \dfrac{134900}{1000} = 135$

$s_T = 30.0$

$T_O = 5$

$H_O : T = T$

$H_1 : T = T$

reject $H_O$ if $t^* > | t \quad |$    $t_{.005,3} = 5.841$

$t^* = \dfrac{224 - .35}{30 \,/\sqrt{4}\,} = \dfrac{89}{15} = 5.933$

$t^* > | t_{\alpha/2} | \therefore$ reject $H_O$

Solve for adjusted $T_1$

$5.841 = \dfrac{224 - T_1}{30 \,/\sqrt{4}\,}$

$T_1 = 136$

AACE PI Threshold Value is set at 136

## CH-54 AACE Threshold Calculation

$n = 4$

$T_O = 125$

$$T_l = \frac{(4)(194)(25)+(125)(4356)}{(4)(25)+4356}$$

$S_O = 25$

$\bar{T} = 194$

$$= \frac{563900}{4456} = 127$$

$S_{\bar{T}} = 66$

$H_O : T_u = T_l$

$H_1 : T_u \neq T_l$

reject $H_O$ if $t^* > |t_{\alpha/2}|$          $t_{.005,3} = 5.841$

$$t^* = \frac{194 - 127}{66/\sqrt{4}} = \frac{67}{33} = 2.03$$

$t^* \not> |t_{\alpha/2}| \therefore$ cannot reject $H_O$

AACE PI Threshold Value is set at 127

OH-6 AACE Threshold Calculation

$n = 4$

$T_o = 125$

$$T_1 = \frac{(4)(166)(25) + (125)(1849)}{(4)(25) + 1849}$$

$S_o = 5$

$\bar{T} = 166$

$$= \frac{247725}{1949} = 127$$

$S_{\bar{T}} = 43$

$H_o : T = T_1$

$H_1 : T_u \neq T_1$

reject $H_o$ if $t^* > t_{\alpha/2}$              $t_{.005,3} = 5.841$

$$t^* = \frac{166 - 127}{43 / \sqrt{4}} = \frac{39}{21.5} = 1.814$$

$t^* \not> | t_{\alpha/2} | \therefore$ cannot reject $H_o$

AACE PI Threshold Value is set at 127

## OH-58 AACE Threshold Calculation

$n = 4$

$T_o = 125$

$S_o = 25$

$\bar{T} = 182$

$S_{\bar{T}} = 24$

$$T_1 = \frac{(4)(182)(25) + (125)(576)}{(4)(25) + 576}$$

$$= \frac{90200}{870} = 133$$

$H_o : T_u = T_1$

$H_1 : T_u \neq T_1$

reject $H_o$ if $t^* > | t_{\alpha/2}|$ 　　　　 $t_{.005,3} = 5.841$

$$t^* = \frac{182 - 133}{24 / \sqrt{4}} = \frac{99}{12} = 4.083$$

$t^* \not> | t_{\alpha/2} | \therefore$ cannot reject $H_o$

AACE PI Threshold Value is set at 133

$n = 4$

$T_o = 125$

$$\frac{T_1 = (4)(206)(25) + (125)(3481)}{(4)(25) + 3481}$$

$S_o = 5$

$\bar{T} = 206$

$S_{\bar{T}} = 59$

$$= \frac{455725}{3581} = 127$$

$H_o : T_u = T_1$

$H_1 : T_u \neq T_1$

reject $H_o$ if $t^* > \mid t_{\alpha/2} \mid$      $t_{.005,3} = 5.841$

$$t^* = \frac{206 - 127}{59 / \sqrt{4}} = \frac{79}{29.5} = 2.678$$

$t^* \not> \mid t_{\alpha/2} \mid \therefore$ cannot reject $H_o$

AACE PI Threshold Value is set at 127

U-21/RU-21   AACE Threshold Calculation

$n = 4$

$T_o = 125$ $\qquad\qquad T_1 = \dfrac{(4)(207)(25) + (125)(3364)}{(4)(25) + 3364}$

$S_o = 25$

$\bar{T} = 207$ $\qquad\qquad\qquad = \dfrac{441200}{3464} = 127$

$S_{\bar{T}} = 58$

$H_o : T_u = T_1$

$H_1 : T_u \neq T_1$

reject $H_o$ if $t^* > |\,t_{\alpha/2}|$ $\qquad t_{.005,3} = 5.841$

$t^* = \dfrac{207 - 127}{58 / \sqrt{4}} = \dfrac{80}{29} = 2.759$

$t^* \not> |\,t_{\alpha/2}\,| \quad \therefore$ cannot reject $H_o$

AACE P1 Threshold Value is set at 127

## UH-1M AACE Threshold Calculation

$n = 4$

$T_o = 125$

$S_o = 5$ $\qquad\qquad T_1 = \dfrac{(4)(177)(25) + (125)(729)}{(4)(25) + 729}$

$\bar{T} = 177$

$S_{\bar{T}} = 27$ $\qquad\qquad = \dfrac{108825}{829} = 131$

$H_o : T_u = T_1$

$H_1 : T_u \neq T_1$

reject $H_o$ if $t* > |t_{\alpha/2}|$ $\qquad t_{.005,3} = 5.841$

$t* = \dfrac{177 - 131}{27 / \sqrt{4}} = \dfrac{48}{13.5} = 3.407$

$t* \not> |t_{\alpha/2}| \therefore$ cannot reject $H_o$

AACE Threshold Value is set at 131

OH-1H/V  AACE Threshold Calculation

$n = 4$

$T_o = 125$

$S_o = 5$         $T_1 = \dfrac{(4)(128)(25) + (125)(676)}{(4)(25) + 676}$

$\bar{T} = 178$

$S_{\bar{T}} = 26$         $= \dfrac{97300}{776} = 125$

$H_o : T_u = T_1$

$H_1 : T_u \neq T_1$

reject $H_o$ if $t^* > \mid t_{\alpha/2} \mid$         $t_{.005,3} = 5.841$

$t^* = \dfrac{178 - 125}{26 / \sqrt{4}} = \dfrac{53}{13} = 4.077$

$t^* \not> \mid t_{\alpha/2} \mid \therefore$ cannot reject $H_o$

AACE PI Threshold Value is set at 125

## UH-60 AACE Threshold Calculation

$n = 4$

$T_o = 125$

$S_o = 5$

$\bar{T} = 200$

$$T_1 = \frac{(4)(200)(25) + (125)(3364)}{(4)(25) + 3364}$$

$$= \frac{440500}{3464} = 127$$

$S_{\bar{T}} = 58$

$H_o : T_u = T_1$

$H_1 : T_u = T_1$

reject $H_o$ if $t^* > |t_{\alpha/2}|$ $\quad\quad t_{.005,3} = 5.841$

$$t^* = \frac{200 - 127}{58/\sqrt{4}} = \frac{73}{29} = 2.517$$

$t^* \nRightarrow |t_{\alpha/2}|$ $\therefore$ cannot reject $H_o$

AACE PI Threshold Value is set at 127

# 7.0 A FAULT TREE APPROACH TO CORROSION CONTROL FOR ARMY AIRCRAFT

# 7.0   A FAULT TREE APPROACH TO CORROSION CONTROL
# FOR ARMY AIRCRAFT

**RTA**     **Reliability Technology Associates**
700 Ravinia Place
Orland Park, IL 60462-3750
(312) 349-9590

October 18, 1988

Dr. Frank A. Iddings
Director, NTIAC
Southwest Research Institute
Post Office Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Subject: Report: "A Fault Tree Approach to Corrosion Control for Army
   Aircraft"
   SwRI Purchase Order No. 19359

Dear Frank:

   This report presents the results of a study to develop a qualitative
fault tree concept approach to corrosion control for Army aircraft. This
approach can be used to evaluate the adequacy of corrosion control efforts and
to perform an independent and objective evaluation of Army aircraft systems to
identify corrosion-related failure modes and those corrosion-related events
and conditions which might lead to safety hazards and/or low reliability.
   Fault tree analysis is a documented process of a systematic nature
performed to identify basic faults and determine their causes and effects. It
involves several steps, among which is the structuring of a highly detailed
logic diagram which depicts basic faults and events that can lead to system
failure and/or safety hazards. From this approach corrective suggestions can
be formulated which, when implemented, will eliminate (or minimize) those
faults considered critical.
   During this study, corrosion in Army aircraft was reviewed to perform a
fault tree analysis. The fault tree diagram on which the analysis is based is
a detailed logic structure that portrays a broad ensemble of possible
corrosion-related faults that can lead to Army aircraft system component
failure during flight. At any point in the tree the lower level events (i.e.,
component faults, maintenance actions, operating procedures and conditions,
etc.) which must occur to precipitate a specific corrosion-related consequence
are connected to the consequence through basic logic elements ("and" gates,
"or" gates, etc.) which portray the essential causal relationships. A
first-cut analysis of the safety level of a corrosion control system can be
based on the relative occurrence of "and" and "or" gates at various levels
within the tree. This is the level of analysis which can be conducted using
the approach described here.
   The following specific engineering tasks and activities were performed
during this study. Based on the review of corrosion in Army aircraft, major
corrosion-related undesirable hazardous events were identified. These events
provided the basis for the fault tree analysis. Then, the fault tree analysis
itself was performed; the logic diagram portraying the corrosion-related basic
faults that can lead to the hazardous events defined was constructed.
Subsequent events, such as component faults, maintenance actions, and

operating conditions that must occur to result in the system hazards, were interconnected through basic logic elements systematically to form the fault tree. The symbols used in constructing the fault tree are shown in Figure 1.

The corrosion-related fault tree prepared using the approach outlined in the previous paragraph is presented in Figures 2 through 5. Figure 2 shows that component failure during flight due to corrosion can be caused by an impending corrosion-related failure, which is not detected prior to the flight during ACE/AACE or preflight inspection or flight operation monitoring, in a component which has not been replaced at a preset time limit. Impending component failure due to corrosion can result from corrosion sufficient to cause component failure which is not accommodated through design, service, or installation. Corrosion sufficient to cause component failure can result from the effect of cumulative dynamic stresses on corrosion present in a static condition; this corrosion can be surface corrosion, galvanic corrosion, intergranular corrosion, stress corrosion, or fretting corrosion.

Figure 3 shows the portions of the fault tree pertaining to each type of corrosion. Surface corrosion can result from the failure to treat corrosion due to the exposure of the surface to corrosive moisture and environmental stresses. Galvanic corrosion can result from the contact of dissimilar metals, through either design error or a breakdown of plated surfaces or improper hardware substitution, in the presence of moisture. Intergranular corrosion can result from the presence of moisture at an imperfectly heat treated component. Stress corrosion can result from the effect of sustained tension stresses in the presence of moisture. Fretting corrosion can result from fretting, through a lack of either lubricant coating between surfaces or vibration control, in the presence of moisture.

Figures 4 and 5 show the portions of the fault tree pertaining to the presence of moisture and corrosive moisture, respectively. In each case moisture may be present due to either entrapment or entrance in the field environment. Entrapment may be induced during either manufacturing or maintenance. If moisture is present in the manufacturing environment, it may become entrapped and not be detected by the quality control inspection. If moisture is present in the maintenance environment, faulty repair or maintenance may lead to moisture entrapment which may not be detected through inspection. Moisture entrance in a field environment where moisture is present may occur as a result of defects induced either due to exceeding design limits previously or during manufacturing with inadequate quality control inspection or during maintenance due to faulty repair or maintenance which is not detected by inspection.

In conclusion, a qualitative fault tree approach to corrosion control in Army aircraft has been developed that can be used to assist in assessing the magnitude of the corrosion problem relative to specific Army aircraft and components and their usage, location, application conditions and maintenance factors and to help to guide a review of nondestructive corrosion inspection techniques that can be incorporated into criteria and guidelines for identifying the types of corrosion failure mechanisms.

If you have any questions on this, please contact me at (312) 349-9590.
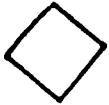
Sincerely,

Dan Henry

C. D. (Dan) Henry III
Program Manager

An event, usually a fault, resulting from the combination of more basic faults and/or conditions and which can be developed further.

A basic fault (usually a specific circuit, component or human error) which can be assigned a probability of occurrence.

A fault not developed further as to its causes because of lack of information, time, or value in doing so.

And gate - the output event occurs only when all of the input events are present.

Or gate - the output event occurs when one or more of the input events are present.

Fault tree continued on another figure.

Inhibit gate - similar to an And gate; however, used to include application of a conditional event.

An event expected to occur in normal operation.

Figure 1    Description of Fault Tree Symbols
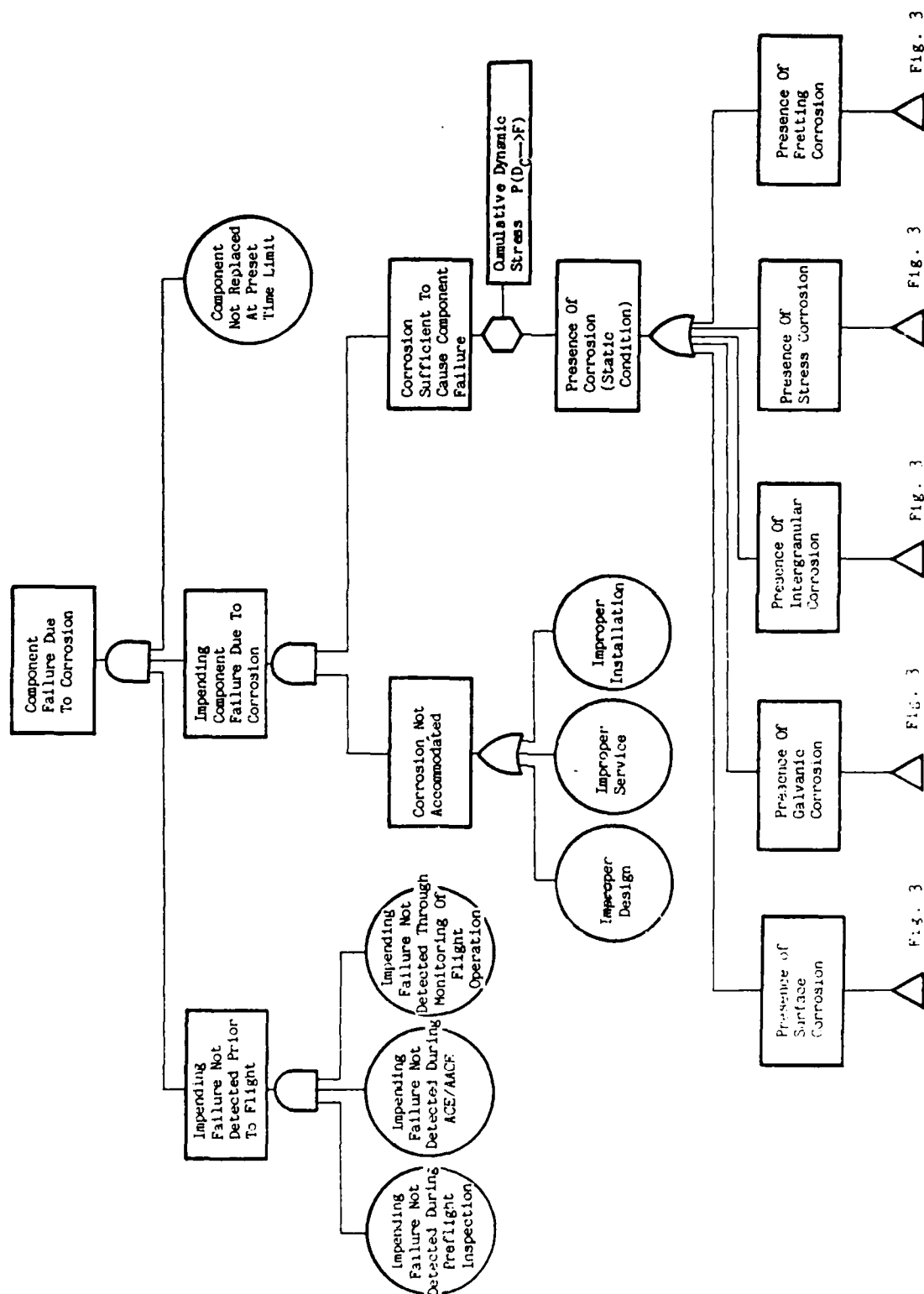
Figure 2  Corrosion-Related Fault Tree
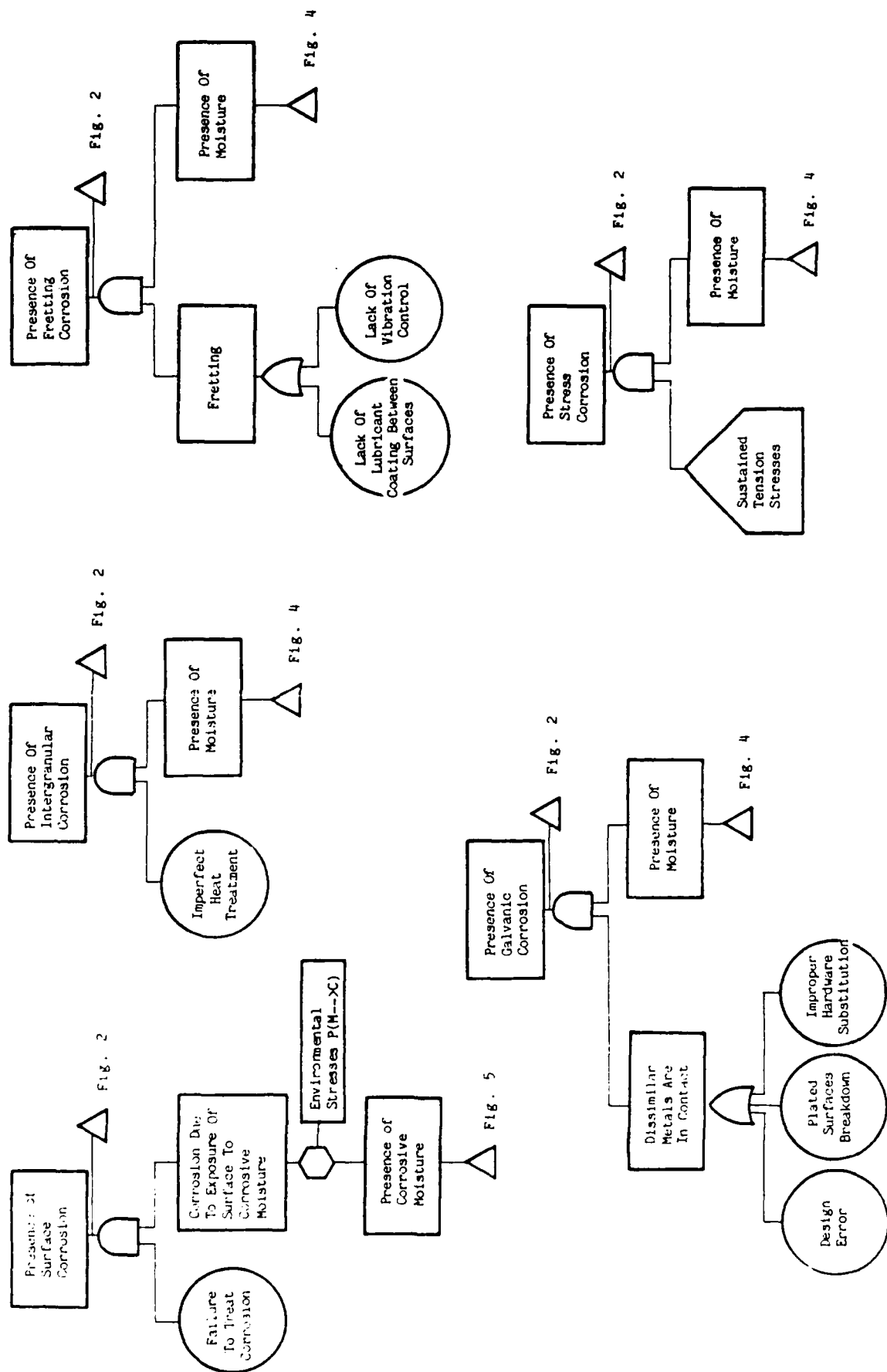
Figure 3  Corrosion-Related Fault Tree (Con't)

Figure 4 Corrosion-Related Fault Tree (Con't)

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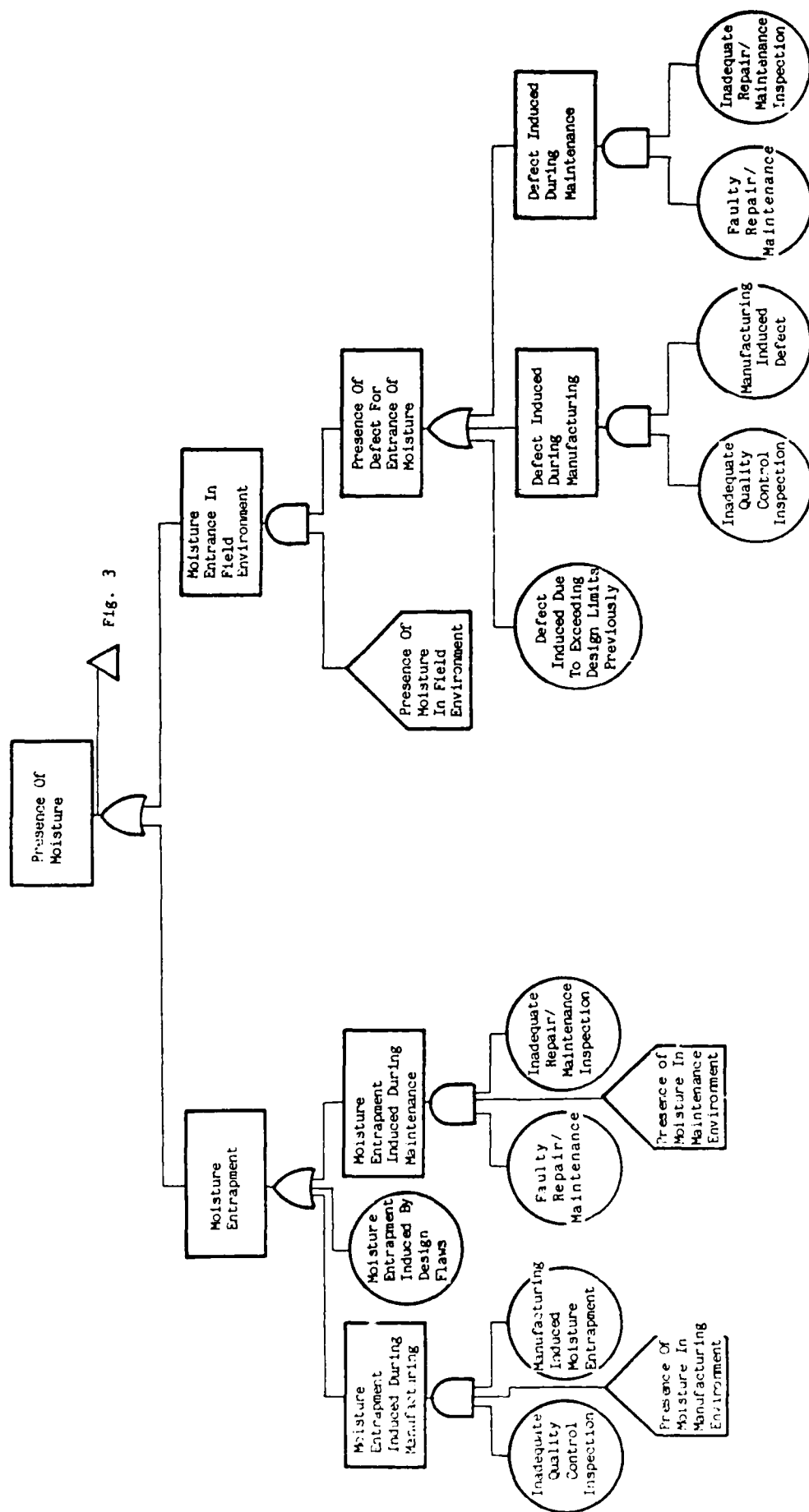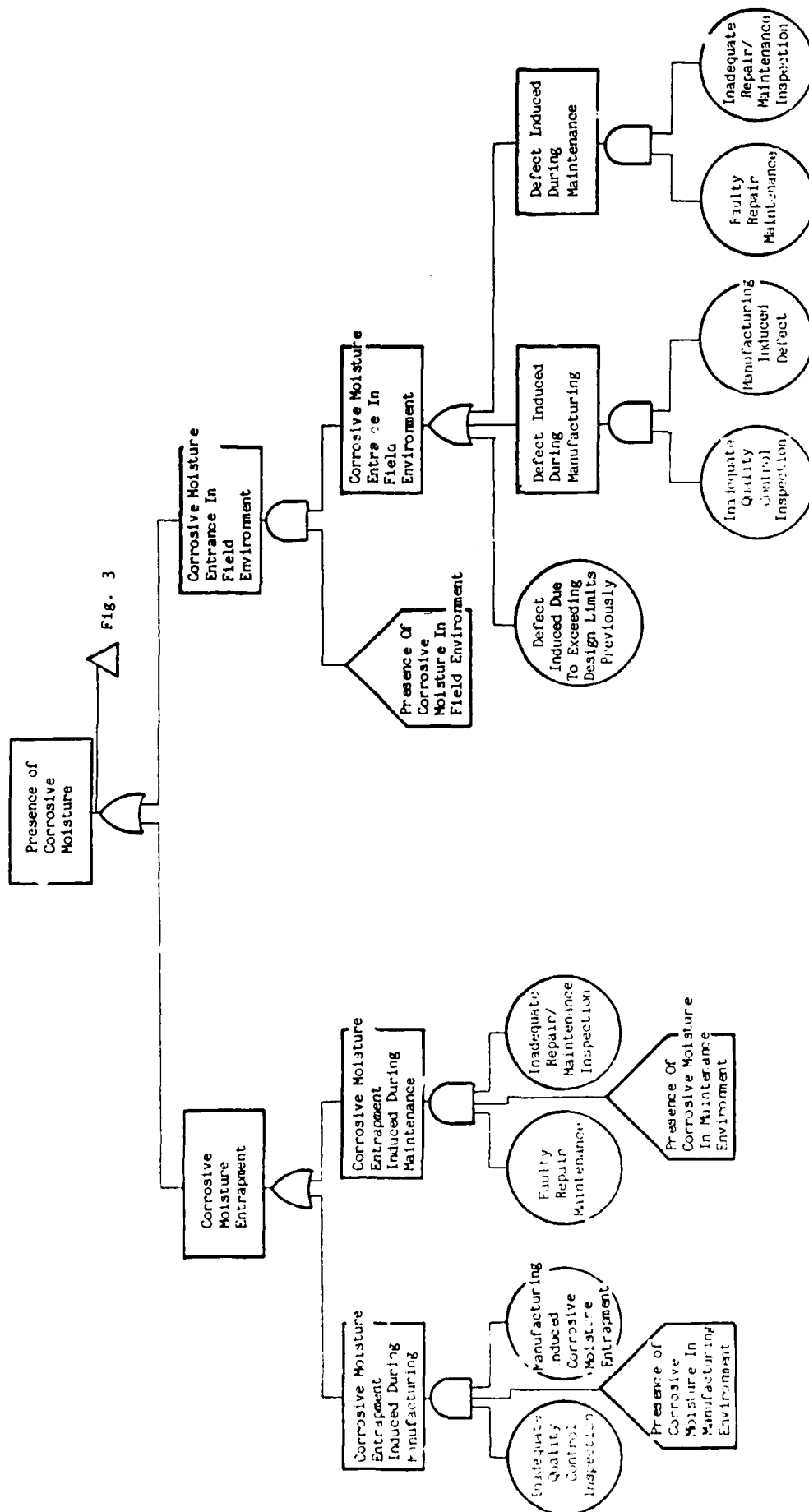
Figure 5   Corrosion-Related Fault Tree (Con't)

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**8.0 A COMPARATIVE ASSESSMENT OF POSSIBLE PLANNING AND CONTROL SYSTEMS FOR CCAD OVERHAUL/NDI OPERATIONS**

# 8.0 A COMPARATIVE ASSESSMENT OF POSSIBLE PLANNING AND CONTROL SYSTEMS FOR CCAD OVERHAUL/NDI OPERATIONS

Prepared for:

Depot Engineering & RCM
Support Office
U.S. Army Aviation Systems Command
Corpus Christi, Texas 78419-6195

Prepared by:

Reliability Technology Associates
700 Ravinia Place
Orland Park, Illinois 60462-3750

Performed as a Special Task under the auspices of the
Nondestructive Testing Information Analysis Center
Contract No. DLA900-84-C-0910, CLIN 0001BM.

October 1988

# FOREWORD

The work described herein was performed for the U.S. Army Aviation Systems Command (AVSCOM), Depot Engineering and RCM Support office (DERSO), as part of AVSCOM's program to assess the extent of corrosion in Army aircraft and its cost, investigate non-destructive inspection (NDI) techniques for corrosion, and formulate specific recommendations for detecting corrosion in new and fielded Army aircraft. The purpose of this specific effort was to provide a comparative assessment of three systems to improve production efficiency and corrosion prevention during overhaul/NDI operations at Corpus Christi Army Depot. It was conducted as part of a Special Task under the auspices of the Nondestructive Testing Information Analysis Center (NTIAC) at Southwest Research Institute (SwRI) under Contract No. DLA900-84-C-0910, CLIN 0001BM. This study was performed under subcontract by Reliability Technology Associates (RTA). At RTA, Dr. C. D. Henry was program manager and principal investigator. Dr Frank A. Iddings was SwRI's technical monitor for the study. At AVSCOM, this study was monitored by Mr. Lewis Neri, who provided the necessary data and other information used as input.

## TABLE OF CONTENTS

## 1.0  PURPOSE

The purpose of this report is to provide a comparative assessment, including the principles and the major similarities, differences, relationships, trade-offs, and requirements, of three systems to improve production efficiency and corrosion prevention during overhaul/NDI operations at Corpus Christi Army Depot (CCAD). These three systems are materials requirements planning (MRP)/manufacturing resources planning (MRPII), just-in-time(JIT)/kanban, and optimized production technology (OPT). Each of these innovative systems challenges old assumptions and ways of doing things. The decision on which approach (or combination of approaches) to adopt to meet current and future needs for overhaul/NDI operations at CCAD, and the implementation of this decision, involves a complex design, huge input requirements, several years of training personnel and the investment of millions of dollars. Therefore an assessment of possible choices is important.

## 2.0 OVERVIEW

### 2.1 Material Requirements Planning (MRP)/Manufacturing Resource Planning (MRPII)

Materials requirements planning (MRP) is a computerized production planning system that attempts to establish precise control over scheduling of production and suppliers. Manufacturing resource planning (MRPII) extends this approach to other functions such as marketing, purchasing, finance, and engineering. The purpose of MRP/MRPII is to make available purchased and manufactured components just before they are needed by the next level of production. It originated in repetitive manufacturing environments, but has been brought to fruition for CCAD-like job shop planning and control.

Conceptually, MRP/MRPII explodes independent demand for a product into the dependent demand for its components. This dependent demand is then time-phased based on established lead times. Lot sizing techniques can be applied at each level of exploded demand. The exploded time-phased lot size demand is then converted to time-phased capacity requirements which must be compared with the available production capacity to test the validity and realism of the production plan. (MRP/MRPII assumes unlimited capacity in all work centers, does not recognize bottlenecks, and is ineffective for capacity planning and control itself. However, possible delays or shortages can be identified in advance using the MRP/MRPII results and affected release dates for orders can be rescheduled to try to meet the promised deliveries.) The actual status of production and purchase orders is compared to the plan to determine which items are ahead or behind schedule, so that priorities in operations and

purchasing can be established and the right amount of materials can be moved at the right time to production levels.    The time-phased production plan provides a common base to coordinate the activities of the functions that interface with operations, e.g. marketing, finance, engineering.    In general the MRP/MRPII calculations are carried out on a week by week basis.

There are two essential requirements for an effective MRP/MRPII:    the ability to develop valid, realistic schedules and tremendous amounts of highly accurate data (a precise demand forecast for each product and an accurate estimate of needed materials for each and every product and component).  Every employee must be thoroughly and strictly disciplined about feeding updates into the system and about always making all planning and control decisions based on MRP/MRPII data.    Otherwise, the MRP/MRPII data system accumulates errors.

In general, in companies with mass-production assembly lines, particularly in those with a history of chaotic inventory situations, MRP/MRPII can help reduce inventories, improve labor and space utilization, and streamline scheduling and receiving operations.    MRP/MRPII focuses management attention on accurate record-keeping, which leads to reduced inventories and improved customer service.


2.2  Just-In-Time (JIT)/Kanban


Just-in-time (JIT)/kanban is both a material flow and production control system and a method of continually improving productivity.    The purpose of JIT/kanban is to have the right material at the right place at the right time while constantly reducing work in progress, lead times, work-in-process inventories, and setup times to an absolute minimum in order to obtain

low-cost, high-quality, on-time production.

As a production control system JIT/kanban establishes daily production rates for a product and then freezes them for a period of time; usually there is a general one-year rough-cut master schedule, a one- to two-month horizon for detailed production scheduling, a ten-day production schedule (which is about 99 percent reliable or fixed), and a daily schedule which is prepared the day before. Month-to-month variations in this schedule are allowed to occur only gradually (in steps of not more than 10%). This detailed production scheduling is done in advance only for final assembly and is the only area in which the computer is utilized as a detailed production scheduling tool. Final assembly is scheduled such that there is an even, consistent flow of work and materials through all upstream work centers (both in-plant and supplier) in the supply chain. When parts are needed at final assembly, they are withdrawn from feeding work centers in small quantities (lot sizes) only as needed. Generally the parts are conveyed in standard containers in which are the fewest parts possible; the optimal quantity (lot size) for a part is just equal to the number of parts for one unit of assembly. The feeding work centers then produce parts in the same quantities that they were withdrawn by final assembly. This production usually requires the consumption of parts produced by the previous work center in the supply chain which triggers the second work center to replace only the parts that were used by the first work center. This process repeats itself down the entire manufacturing supply chain, so that each action by final assembly results in a ripple effect back through the feeding work centers, both in the plant and at suppliers' plants. (Suppliers' plants act like extended storage facilities of the plant.) JIT/kanban, then, is a pull system; the user work center pulls parts from the supplier work center on a lot-for-lot basis.

("Kanban" is the Japanese word for the marker which controls the sequencing of parts through the work centers.) Each work center is closely linked to the work centers that it feeds and to the work centers that supply it parts (including suppliers' plants). There are short lead times (small inventories) at each stage, so, if for some reason a stoppage occurs at any operation, the entire system very shortly grinds to a halt for lack of work; no extra production or inventories are permitted.

As a productivity improvement system JIT/kanban forces recognition and resolution of bottleneck operations. Once a plant is in balance - there are no critical shortages in the system and no departments are working excessive amounts of overtime - either work-in-process inventory is withdrawn from the production floor or the assembly schedule is increased without increasing resources in the system. Either process will eventually cause one of the production resources to become a constraint on the total system output. This bottleneck manifests itself by either having to work large amounts of overtime or by being unable to produce sufficient parts to keep the next work center running. The organization then focuses on resolving the problem. Once that problem is resolved and a steady state condition has been reestablished, then additional inventory is withdrawn from the plant floor or the assembly schedule is increased until the next constraint appears. The process is then repeated.

Through these two aspects of JIT/kanban, production control and productivity improvement, stock between successive processes is eliminated and idle equipment, facilities, or workers are minimized.

Beyond the strict definition that these two aspects give to JIT/kanban, the JIT/kanban philosophy involves several related aspects. Stockrooms are emptied and all inventory is brought onto the shop floor. The shop floor is

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arranged into cells rather than according to machine function. The number of suppliers is limited and JIT/kanban delivery schedules are worked out with them. Plant floor size is limited. Quality control is monitored at stations along the assembly line rather than only at the end of it.

Two types of requirements must exist for a successful JIT/kanban system. First a unique type of "cultural" environment must exist. Responsibility and authority for shop floor production control and productivity improvement must be placed on the workers and first-line supervisors who must be motivated. There must be an atmosphere of strict discipline, close cooperation and mutual trust between the workforce and management and an attitude that encourages any actions that aid the continual flow of parts - including helping other people when they fall behind, doing different types of jobs, reducing setup times, working overtime and temporarily stopping the process/assembly line. JIT/kanban usually includes quality circles that work to cut down on lot sizes, reduce lead and setup times, help solve supplier problems, and minimize scrap losses. Secondly the production environment must meet several requirements: production rates at final assembly must be even, daily production schedules must be virtually identical, a large number of production setups must be made (to achieve the assembly schedule mix which maximizes flow of parts) so setup times and costs must be at negligible levels, actual daily production must closely approximate the schedule, and parts should be produced and moved in standard quantities in the smallest containers possible.

For mass-produced items (which generally comprise about 60% to 70% of all the items regularly used in large-volume products), then, the JIT/kanban approach can increase labor productivity and reduce inventories (and related costs), quality rejection rates, necessary plant space, and paperwork for planning and control. A JIT/kanban system can be operating in about two years

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and achieves optimum results in five to ten years.


## 2.3  Optimized Production Technology (OPT)


The OPT system uses a proprietary computer software package to calculate near-optimum schedules and sequences of operations for all operational work centers, taking into account priorities and capacities.

OPT begins with the construction of a model of the operational environment.  The conventional files typically found in MRP/MRPII systems are converted into a product network.  This network becomes the model of operations, describing how operations are carried out, the competition for resources, and the interrelationships between parts going into an assembled product.  OPT then utilizes the production requirements and available operational resources to produce optimized schedules and generate materials requirements.  OPT works by testing the existing work load, identifying critical or bottleneck resources and then using the proprietary algorithm, called the OPT "brain", to schedule these resources and produce an optimized schedule.  Priorities for each operation are determined using a weighted function of (actually a set of management coefficients for) a number of important criteria.  Once the optimized schedule is determined for the critical resources, then this schedule is used as the input to the noncritical resources.  These resources are scheduled using an MRP system.

OPT requires detailed information about inventory levels, product structures, routings, and setup and operation timings for each product procedure.

For situations that involve a few fundamental products with large batch sizes, but each with only a few operations, OPT can be implemented within two

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to three months, can produce a one day's schedule in minutes, providing 1000 work instructions within 30 seconds, and can increase overall output and reduce work in progress and inventories.

In some ways, OPT integrates the best of MRP/MRPII - a computerized data-base system - and JIT/kanban - improvements in flow and the elimination of waste. Unlike MRP/MRPII and JIT/kanban, with OPT employee attitudes do not have to be changed.

## 3.0 COMPARISONS

### 3.1 General

As can be seen from the discussion above MRP/MRPII allows for advance planning for medium-inventory, mass-production companies, but at a cost in flexibility and informality. JIT/kanban keeps inventory costs down and involves employees, but requires well-structured supply lines and cooperative workers. OPT focuses on clearing up bottlenecks in operational processes, but can adversely affect nonbottleneck areas and is a proprietary system.

### 3.2 Working Environment of Originating Country

MRP/MRPII originated in the United States; JIT/kanban, in Japan; and OPT, in Israel.

In the United States there is no land space restriction; factories are usually very spread out. Land space is a problem in Israel; it is very restrictive in Japan and becomes a major production constraint.

The major market for products manufactured in the United States is within the country; the major markets for the products of both Japan and Israel are outside the producing country. Therefore both Israel and Japan are extremely quality conscious - it is very expensive to make repairs on or replace products which are thousands of miles overseas. In the United States repairs are not that expensive; sometimes it is desirable to make lower quality products to generate replacement profits.

The United States has a philosophy of product variability - the customer is offered as many options as possible in the design and development of

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products. Therefore, United States factories are large with unused space to allow a large build-up of inventory necessary to handle product variability requirements. Japan, on the other hand, restricts product output to only a few selections because product modifications are difficult in the Japanese environment and it is difficult to give efficient turnaround response time on customized products for overseas markets. Israel allows more product variability than Japan.

United States industry places emphasis on individual employee productivity while the Japanese and the Israeli have a philosophy of the productivity of the facility as a whole. The United States costs jobs in terms of standard pieces produced per hour for each individual employee; this puts the employee under a time restraint to build products, whether they are needed or not, with speed rather than quality.

In Japan and Israel quality is a part of a employee's functions, e.g. Japanese workers become involved in quality through quality circles. Employee evaluation is based on how closely total production matches required production without generation of excess inventory or waste.

MRP/MRPII systems generate a list of materials required to produce a specific number of output units; this in turn generates purchase orders and production orders. Large quantity factors (called scrap factors) are often inserted to generate excess needed materials at the purchasing end. This is referred to as a "push" system.

In JIT/kanban systems, which are "pull" systems, materials are not fed into the production cycle until finished product is actually required. Product requirements, not forecasts, trigger production. This requires very short lead times.

In OPT production is scheduled on a "bottleneck" basis. Bottleneck areas

in a facility are analyzed and emphasized. Production is planned so that bottleneck work centers are utilized to the maximum and nonbottleneck work centers keep the bottleneck work centers working at full production all the time.

## 3.3 Employee Performance

Indirectly, the JIT/kanban system addresses the problems of keeping employees disciplined and motivated; making sure they are constantly feeding the system with updated information; and getting them to accept changes in procedures, organizational structures, paperwork, and cost accounting. It is a simple and transparent system. Employees are responsible for making the system work.

MRP/MRPII offers no challenge to employees, but requires that they be extremely disciplined and committed at all levels.

OPT requires moderate discipline and limited data accuracy. Problems with employees get resolved indirectly through procedural, cost-accounting, and work-method changes.

## 3.4 Production Loading

MRP/MRPII sequences tasks as if the plant has infinite resources available and then adjusts the schedules by adding a capacity requirements planning step; this two-step procedure is not as efficient as developing optimal schedules in one step. Both JIT/kanban and OPT schedule production assuming limited capacity. Kanban cards control capacity in JIT/kanban; bottlenecks, in OPT. OPT allows more variable constraints than MRP/MRPII and

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merges MRP/MRPII and capacity requirements planning functions into one tool.

3.5 Batch Sizing

MRP/MRPII systems assume that a part passes all stages of production in a fixed-sized batch. Batch size is kept larger than necessary in order to offset costs incurred by large setup times. A reduced setup cost is allocated per part. Increased batch sizes increase product lead time, which increases interest and storage costs which, in turn, translate into increased overall cost.

In JIT/kanban all setup times are reduced to a minimum so that it will not be a significant factor in determining batch sizes; batch sizes can then be kept small.

In OPT variable batch sizes are computed. Setup time is reduced to a minimum in bottleneck work centers, maximizing output in these areas and of the whole facility.

3.6 Production Waves

Production waves in an MRP/MRPII system are balanced through use of safety stock. In JIT/kanban, the entire production sequence is forced to stay in synchronization and production waves are not allowed to occur. In OPT, production waves are prevented by tighter scheduling and through the use of safety capacity.

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## 3.7 Data Accuracy

In MRP/MRPII data accuracy is critical throughout the entire system; in OPT, data accuracy is only critical in the bottleneck areas and in their feeder areas. Both MRP/MRPII and OPT require computer systems; OPT is typically faster than MRP/MRPII in generating production schedules.

In JIT/kanban there is no need for data accuracy; computer systems are not needed.

## 3.8 Scheduling

OPT supplies a more complete schedule than JIT/kanban; however, JIT/kanban supplies it faster. OPT's time performance in developing schedules is faster than MRP/MRPII.

## 3.9 Flexibility

JIT/kanban is the most flexible because of its minimal batch sizes and low inventory levels. OPT schedules lower levels of inventory and allows for flexible batch sizes and, thus, allows for more flexibility in production than MRP/MRPII.

JIT/kanban generally requires a total reorganization of the facility; OPT offers much of the same flexibility without a reorganization. OPT can be phased into the operation, so the entire facility is not necessarily affected by installation of an OPT system. OPT allows for parallel operation with an MRP/MRPII system so the proper operation of an OPT system can be assured.

3.10   Cost

The benefits of a completely simulated production plan can only be realized with OPT.   MRP/MRPII is too complex, and JIT/kanban is not complete enough for simulation planning.

MRP, because of its high data accuracy requirements, is the most costly. JIT, because of its negligible data requirements, is the cheapest.

3.11   Other Comparisons

MRP/MRPII has a number of shortcomings, including rigid lot-sizing rules, rigid average queue times, an inability to split lots or send ahead partial lots, sequential (rather than simultaneous) date setting and capacity requirements calculations, iterative load balancing to eliminate overloads, and a lack of finite scheduling logic.

In terms of OPT, it appears that the OPT production planning and inventory control technique has an improved ability for production planning, compared to MRP/MRPII.

OPT has a simplified technique for production scheduling, compared to MRP/MRPII.   Schedules are not as time-consuming to set up.   Schedules do not require as much data.   Less accuracy is required in the data.   Less computer processing capability is required.   Less people time is required to analyze the schedule.

The user portion of OPT is less complex than that of MRP/MRPII.   The internal mathematical technique contains additional sophistication that makes the system user's job easier.   Less user knowledge is required.

OPT gives a more rapid projection of schedule, compared to MRP/MRPII.

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These quicker schedules allow quicker modifications of the schedules and therefore more flexibility in the schedules. Schedules changes can occur in a few hours rather than days. Quicker schedule development allows simulation to be used in the scheduling process.

OPT analyzes plant production, which MRP/MRPII does not do. Bottlenecks in the production process are specifically defined, so improvements are easily made on the bottlenecks. Simulation can be used to test variations in plant output and how this effects plant load. Capacity planning can be simulated in OPT.

In addition, actual finite resources are taken into account in OPT. OPT simultaneously maximizes production output and minimizes work-in-progress inventory as a basis of the optimization in the OPT mathematical technique. Therefore, increased production output, using the same resources, and reduced work-in-progress inventory are possible with OPT. Smaller batch sizes are calculated based on profitability in OPT rather than from a set formula in MRP/MRPII; MRP/MRPII has rigid lot-sizing rules. Finally, the OPT scheduling system allows for finite control of the resources on the short term.

On the other hand, OPT requires a plant reorganization, including a conceptual reorganization, replacement of data processing systems, a changed management style, new reporting systems, and equipment changes and movement. Costing and accounting systems will be disrupted by OPT because efficiency can no longer be calculated, job cost control data have been restricted in some areas, and performance evaluations no longer exist. Users will be disrupted and will need to be retrained; new reports will need to be developed for data processing and accounting to handle the new information base. In addition, OPT produces a tighter schedule, allowing less ability to accommodate production errors. Also, the financial analysis systems have been changed.

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OPT can be compared to JIT/kanban in several areas. Both OPT and JIT/kanban are geared to reducing inventories and identifying bottlenecks. OPT is a computerized system while JIT/kanban is manual. With OPT, then, bottlenecks and the impact of alternate approaches can be analyzed in advance without creating problems on the shop floor. The use of workers, materials, and machines is optimized to maximize the utilization of critical resources, maximize plant output and minimize work-in-process inventory and manufacturing times. OPT can also be used more universally than JIT/kanban which is applicable only in repetitive manufacturing with fairly stable demand. OPT can also be used in job shop and process industries. A key difference between OPT and JIT/kanban is that JIT/kanban maintains a logistical chain between operations while OPT has a logical one.

## 4.0 COMBINATIONS

As seen from the previous discussion, each production scheduling system has advantages and disadvantages. A combination approach could use the best of each system. It has already been noted that OPT can interface with a standard MRP/MRPII system so that OPT-generated schedules can be coordinated with non-bottleneck scheduling. MRP/MRPII is often used with JIT/kanban to ensure that raw material is available for the JIT/kanban process. Some MRP/MRPII software packages now offer support for JIT/kanban.

## 5.0 CONCLUSION

Theoretically and technically, each system discussed in this report appears to be sound in its own way and should be able to accomplish low-cost, high-quality, on-time production. Both JIT/kanban and OPT seem to be more productive than MRP/MRPII, and OPT is seen as more complete than JIT/kanban in that it includes many features of JIT/kanban and additional benefits as well. Combinations of the systems are possible and this combining of approaches may be the key to the future in this area. In the final analysis, however, CCAD will have to look at the facts and comparisons presented in this report and at the various trade-offs and make a decision based on the CCAD-specific situation and circumstances.

**9.0   A REPORT ON THE STATUS OF THE DEVELOPMENT OF AN NDI
ORIENTED CCAD MANUFACTURING MODEL**

# 9.0 A REPORT ON THE STATUS OF THE DEVELOPMENT OF AN NDI ORIENTED CCAD MANUFACTURING MODEL

A REPORT ON THE STATUS OF THE DEVELOPMENT

OF AN NDI ORIENTED CCAD MANUFACTURING MODEL

Prepared for:

Depot Engineering & RCM
Support Office
U.S. Army Aviation Systems Command
Corpus Christi, Texas 78419-6195

Prepared by:
Reliability Technology Associates
700 Ravinia Place
Orland Park, Illinois 60462-3750

October 1988

FOREWORD

The work described herein is being performed for the U.S. Army Aviation Systems Command (AVSCOM), Depot Engineering and RCM Support Office (DERSO), as part of AVSCOM's program to assess the extent of corrosion in Army aircraft and its cost, investigate non-destructive inspection (NDI) techniques for corrosion, and formulate specific recommendations for detecting corrosion in new and fielded Army aircraft. The purpose of the specific effort for which this report gives the status is to develop an NDI oriented manufacturing model for Corpus Christi Army Depot (CCAD) into which candidate NDI corrosion prevention methods can be incorporated for validation. It is being conducted as part of a Special Task under the auspices of the Nondestructive Testing Information Analysis Center (NTIAC) at Southwest Research Institute (SwRI) under Contract No. DLA 900-84-C-0910, CLIN 0001BM. This study is being performed under subcontract by Reliability Technology Associates (RTA). At RTA, Dr. C. D. Henry is program manager and principal investigator. Dr. Frank A. Iddings is SwRI's technical monitor for the study. At AVSCOM, this study is being monitored by Mr. Lewis Neri, who is providing necessary data and other information used as input.

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## FIGURES

## 1.0 INTRODUCTION

This report gives the results to date of a special investigation involving determining how to proceed in developing an NDI oriented manufacturing model for Corpus Christi Army Depot (CCAD) into which can be incorporated candidate NDI methods that would improve the prevention of corrosion during CCAD's overhaul/NDI operations. Very early in the investigation it was decided to concentrate effort on structuring a flexible manufacturing system (FMS) for CCAD.

The investigation has involved, then, conducting a literature search, which is on-going, to determine the nature of flexible manufacturing systems and the methods used in managing the systems. FMS is also being studied in detail by visiting several strategic areas where there is expertise or interest in FMS with emphasis on military applications of FMS. Following the literature search, the visits, and the preliminary work reported herein, a model will be developed to simulate the FMS environment. The model will be used to determine the ideal structure of an FMS and its operational relationship to a major customer. Then, a flexible manufacturing system will be structured at Corpus Christi Army Depot. This model will be validated and an economic analysis will be made.

## 2.0  FLEXIBLE MANUFACTURING SYSTEMS

### 2.1  Background

The general problem addressed by flexible manufacturing systems is that U. S. manufacturers are experiencing difficulty in remaining competitive in the new world marketplace which has developed over the past several years. While the quality of U. S. produced goods has in the past been the standard of the world, new market demands and competition from abroad have raised the standards required to effectively compete in current and future markets.  New and innovative products are being introduced into the market at an ever increasing pace so that a manufacturer can no longer assume a product life of ten to twenty years nor afford to take five to ten years to introduce new product lines.  Meeting these challenges of competition, quality, and new and innovative products is essential for commercial viability in competitive world markets.  These challenges can be met by flexible manufacturing systems, which can run virtually 24 hours a day, but with short turnaround times, and can make a great variety of specialty products with very short setup times.  With flexible manufacturing systems, economies of scale, improved quality, and adaptability to changing needs can be achieved.

### 2.2  Description

A flexible manufacturing system is an integrated computer-controlled complex of numerically controlled machine tools, automated material and tool-handling devices, and automated measuring and testing equipment that, with a minimum of manual intervention and short change-over time, can process any product belonging to certain specified families of products within its

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stated capability and to a predetermined schedule. Such systems permit the continuous manufacture of different items within a family of parts in small batches within a dedicated facility. They use the concept of integrated raw material storage, robot part picking, part transportation by conveyors, and direct numerical control machining. Everything is linked together in such a way that the parts being worked on can travel from raw material storage to finished goods storage in different sequences under the control of computers.

A central FMS computer schedules and tracks all production and material movement in the FMS. Based on a family of similar parts, an FMS can be reprogrammed quickly through downloaded instructions from the central computer to individual machines, conveyors, and robots to perform a new set of tasks.

Flexible manufacturing systems, then, are automated production systems for the manufacture of mid-volume and mid-variety products (or components) with minimal setup times. They consist of several numerically controlled machines integrated with automated workpiece and tool-transfer and handling systems, which are connected to some form of automated warehouse and tool-storage system. All the subsystems of the FMS are controlled by the central computer which downloads numerical control programs to individual machine tools, controls workpiece flow, and generates performance reports. The functions of scheduling, part-program selection, cutting-abnormality detection, tool-breakage detection, tool-wear compensation, pallet retraction, measuring, and self-diagnosis are all carried out automatically.

2.3 Advantages of Flexible Manufacturing Systems (General)

There are several advantages to flexible manufacturing systems.

In flexible manufacturing systems, production can be continually adjusted

to changing needs and to new products, largely by software reprogramming. This allows continuous incremental adaptation to changing requirements for products and systems that otherwise would require major retooling and down times. The high entry costs for new product manufacture are greatly reduced because a dedicated plant operating at partial capacity is no longer required. Therefore, machine utilization is increased and there is quick reaction to market and design changes. There is a reduced time to market for a product.

Flexible manufacturing systems allow just-in-time manufacturing and delivery. This substantially reduces the costs of inventory, but with instant response to customer needs.

Labor cost savings form a major motive for investing in FMS. These savings are realized mainly through a reduction of direct labor in areas where FMS is employed. Indirect labor costs may also be reduced.

Flexible manufacturing allows improved and consistent quality control and reproducibility.

Flexibility manufacturing allows better management control over the manufacturing process and institutionalizes the management of continuous change that will be necessary for industrial survival.

7.4 Military Benefits of Flexible Manufacturing Systems

The focus in this special investigation has been on military applications of FMS. The military benefits of FMS relate more to readiness than to cost. Multiple FMS facilities could provide military emergency surge and sustained capacity in national emergencies at minimal cost. The geographical dispersion of FMS facilities would reduced vulnerability to sabotage or other forms of attack. Inventories of obsolescing military spare

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parts would be reduced, reducing military stockpile costs. The elapsed time for introducing new defense equipment or systems utilizing the latest in new technology would be reduced.

2.5 Barriers To Implementation of FMS

There are several major obstacles to success in the implementation of FMS.

The source of most of the problems in making FMS a reality is integration. Many of the major advantages of an FMS, its reduction of lead time, its predictability of operation, its consistency of results, derive from its integration and automation of multiple elements into a complete system. To achieve the integration required, the existing infrastructure of the implementing organization may have to be altered. For example, manufacturing and engineering groups may be required to work hand-in-hand to achieve the necessary integration; to facilitate cooperation, performance measures or some form of incentive may be required. Organizational inertia is a principal obstacle to achievement of the integration needed to implement FMS. Sometimes rigid corporate rules perpetuate old-fashioned approaches to manufacturing and represent a significant barrier to successful integration.

Software integration is another major problem in implementing FMS. The three types of software (business - accounting, production scheduling; manufacturing - route sheets, machining instructions; and engineering - bills of materials, drawings) need to be able to communicate with each other: the facility's production and scheduling system has to interface with the FMS scheduling system and the FMS has to interface with engineering. There are problems in obtaining software, debugging it, interfacing it, maintaining

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(updating) it and solving compatibility problems between the different conventions used in the systems.

Another integration-related problem is the pressure FMS places on interfacing subsystems. The entire FMS must be optimized, not individual processes. It must be recognized that each machine no longer performs independently on its own. In FMS, inefficiencies such as appreciable downtime cannot be tolerated since problems in one stage of the process immediately affect the performance of the entire FMS. The ramifications of a machine breakdown are far-reaching because many times in an FMS there is no way to compensate for it and the entire FMS may be down until a single machine can be gotten up and running. The difficulty in providing adequate maintenance to prevent machine breakdowns is a barrier to FMS.

FMS also places pressure on systems interfacing with it, both within the plant and external to the plant, such as subcontractors and other vendors. Inventory reductions and changes in product quality can add to the cost and schedule problems of interfacing systems.

Human issues represent the biggest problem in implementing FMS. One aspect of this issue is the resistance to change due to the inertia and familiarity of old procedures and conventional methods of operation as discussed previously. Both custom, as well as the formal and informal reward and incentive systems, work against FMS implementation. Another aspect of the issue, a major problem hindering the success of FMS, is the shortage of suitable manpower. There is a serious shortage not only of engineers, but also of technicians and craftsmen. The difficulty of providing proper training for people is another barrier to FMS implementation.

One significant technical barrier to the successful implementation of FMS, especially untended FMS, is the general lack, at this time, of tooling

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automation. Automation is needed in tool transport and changing, tool identification and recognition, tool monitoring, tool storage, and tool management.

Another barrier to FMS implementation is that management accounting systems have failed to keep pace with recent manufacturing technology like FMS. The accounting problems of FMS are caused by the way standard accounting practice treats some of the large early expenditures, the long delays between the expenditures and the resulting sales, and the difficulty in relating expenditures to specific sales.

Government regulations may also pose a barrier to FMS implementation. This possibility is still being investigated.

## 3.0 STRUCTURING A FLEXIBLE MANUFACTURING SYSTEM AT CORPUS CHRISTI ARMY DEPOT

Corpus Christi Army Depot (CCAD) performs repair, overhaul, modification, and retrofit of airframes, aircraft components, systems, subsystems, and related items for UH-1, AH-1, OH-6, OH-58, CH-47, and UH-60 rotary aircraft. The parts necessary to carry out these functions are, in general, supplied by the "customer" on whose aircraft the functions are carried out. CCAD's primary "customer" is the U. S. Army Aviation Systems Command (AVSCOM). By law CCAD may not manufacture parts for which the "customer" can get a "good buy". By U. S. Army regulation, CCAD may not even manufacture a part on which the "customer" cannot get a "good buy" unless such "local manufacture" is specifically authorized by official message. At present there are about 3500 AVSCOM items for which no one has submitted a bid because of the low volume or high required technology of the part. Most of these are routine items which can be manufactured by conventional means.

Occasionally, in the course of its operations, CCAD incurs critical shortages of certain parts which cause work stoppages due to the shortages. This impacts readiness. As of July 15, 1988, there were 239 critically short parts. There are a variety of reasons for these shortages. Depending on the reason, "local manufacture" could be authorized for certain of these parts. Because of the low volume and the short lead time, such locally manufactured parts would be good candidates for a flexible manufacturing system.

An additional dimension is added to the situation if a critically short part also happens to be a flight safety part. A flight safety part is any part, assembly or installation whose failure, malfunction or absence would cause loss of or serious damage to an aircraft and/or serious injury or death to the occupants or inability to release external stores. In addition to

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involving small lot size and a required rapid response to demand, a critically short flight safety part has unique critical requirements and requires high quality and reliability. These critically short flight safety parts need to be produced quickly, with high quality and low cost, and on time. They would be prime candidates for a flexible manufacturing system.

As of July 15, 1988, there were 29 critically short flight safety parts at Corpus Christi Army Depot. These are listed in Table 1. These 29 items are being investigated further to determine the specific reasons for their being critically short and if any of them can be locally manufactured per law and/or U. S. Army regulation (or if permission to locally manufacture can be sought). Further work is also being carried out to group these 29 critically short flight safety parts into part families.

As part of this investigation, the application of a flexible manufacturing system to critically short flight safety parts will be explored by developing a model to simulate an FMS environment at CCAD. The model will provide a means for planning, programming, and controlling an FMS. The model will simulate a manufacturing environment for one or more selected critically short flight safety parts, determine the ideal structure of an FMS, and determine its operational relationship to a major customer.

Early in this special investigation, some preliminary work was done on identifying the required processes and controls and developing an overall model for one representative flight safety part - the UH-1 drag brace rod end clevis (which is no longer on the critical shortage list). This part is shown in Figure 1. Figure 2 shows the current clevis manufacturing process. Figure 3 shows a conceptual clevis FMS model.

Another portion of this special investigation involved determining the CCAD resources available for structuring an FMS at CCAD. CCAD has a number of

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Table 1
Critically Short Flight Safety Parts
Corpus Christi Army Depot
July 15, 1988

UH-1 Structural Support Block (NSN 1560-00-409-9146)
UH-1 Support Arm Assembly (NSN 1560-00-625-0149)
UH-1 Engine Bipod Assembly (NSN 1560-00-967-1752)
OH-58 Main Yoke Assembly (NSN 1615-00-120-0480)
UH-1 Rotary Hub Assembly (NSN 1615-00-133-6872)
UH-1 Plate Set (NSN 1615-00-454-8780)
UH-1 Tail Case Assembly (NSN 1615-00-735-6560)
CH-47 Pin Assembly (NSN 1615-00-740-6477)
UH-1 Hydraulic Pump Cover Assembly (NSN 1615-00-795-0662)
UH-1 Swashplate Support Assembly (NSN 1615-00-856-3919)
UH-1 Main Transmission Main Case Assembly (NSN 1615-00-874-0857)
AH-1 Inner Swashplate Ring (NSN 1615-00-914-6162)
AH-1 Main Housing Assembly (NSN 1615-00-921-5500)
OH-58 Main Rotor Grip (NSN 1615-01-098-7496)
AH-1 Main Rotor Composite Blade (NSN 1615-01-177-5862)
T63 5th & 6th Compressor Rotor Wheel (NSN 2840-00-242-4472)
T63 6th Stage Compressor Rotor Wheel (NSN 2840-00-613-3016)
T53 Retainer Plate (NSN 2840-00-925-4146)
T63 Compressor Tie Bolt (NSN 2840-00-940-9992)
T53 1st Turbine Blade (NSN 2840-01-009-3717)
T53 No. 3 & 4 Bearing Housing (NSN 2840-01-011-5045)
T53 1st Turbine Blade (NSN 2840-01-029-8740)
T63 2nd & 3rd Compressor Rotor Wheel (NSN 2840-01-039-4729)
T63 1st Stage Compressor Rotor Wheel (NSN 2840-01-039-5823)
T700 Pressure & 0 Speed Unit Valve (NSN 2915-01-171-7761)
AH-1 Transmission Planet Pinion Gear (NSN 3020-00-461-1750)
OH-6 Spur Gear (NSN 3020-00-945-5596)
UH-1 Tail Rotor Drive Pinion Assembly (NSN 3040-01-011-1461)
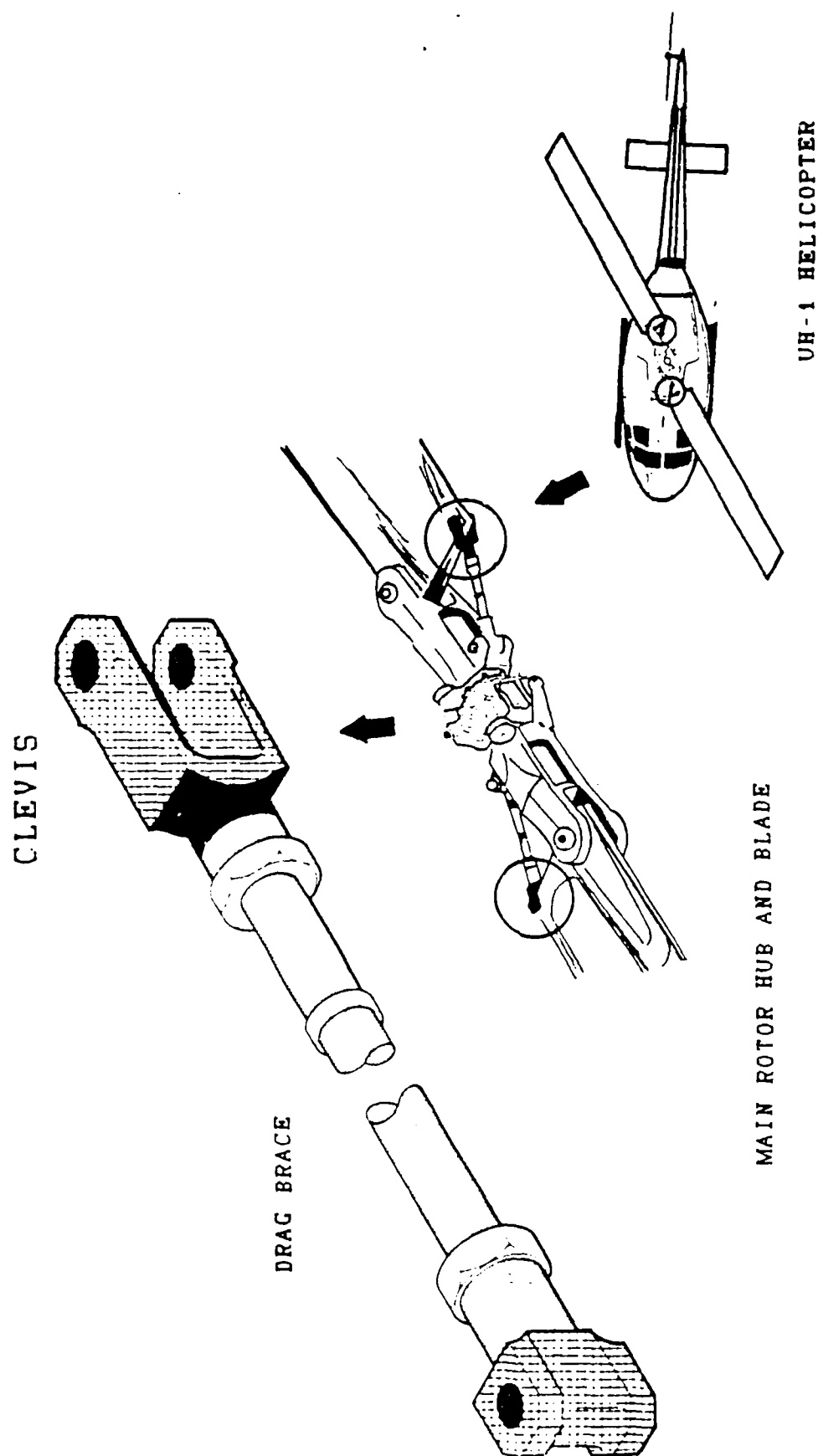UH-1H Plain Encased Seal (NSN 5330-00-753-4432)

NSN = National Stock Number

CLEVIS

DRAG BRACE

MAIN ROTOR HUB AND BLADE

UH-1 HELICOPTER

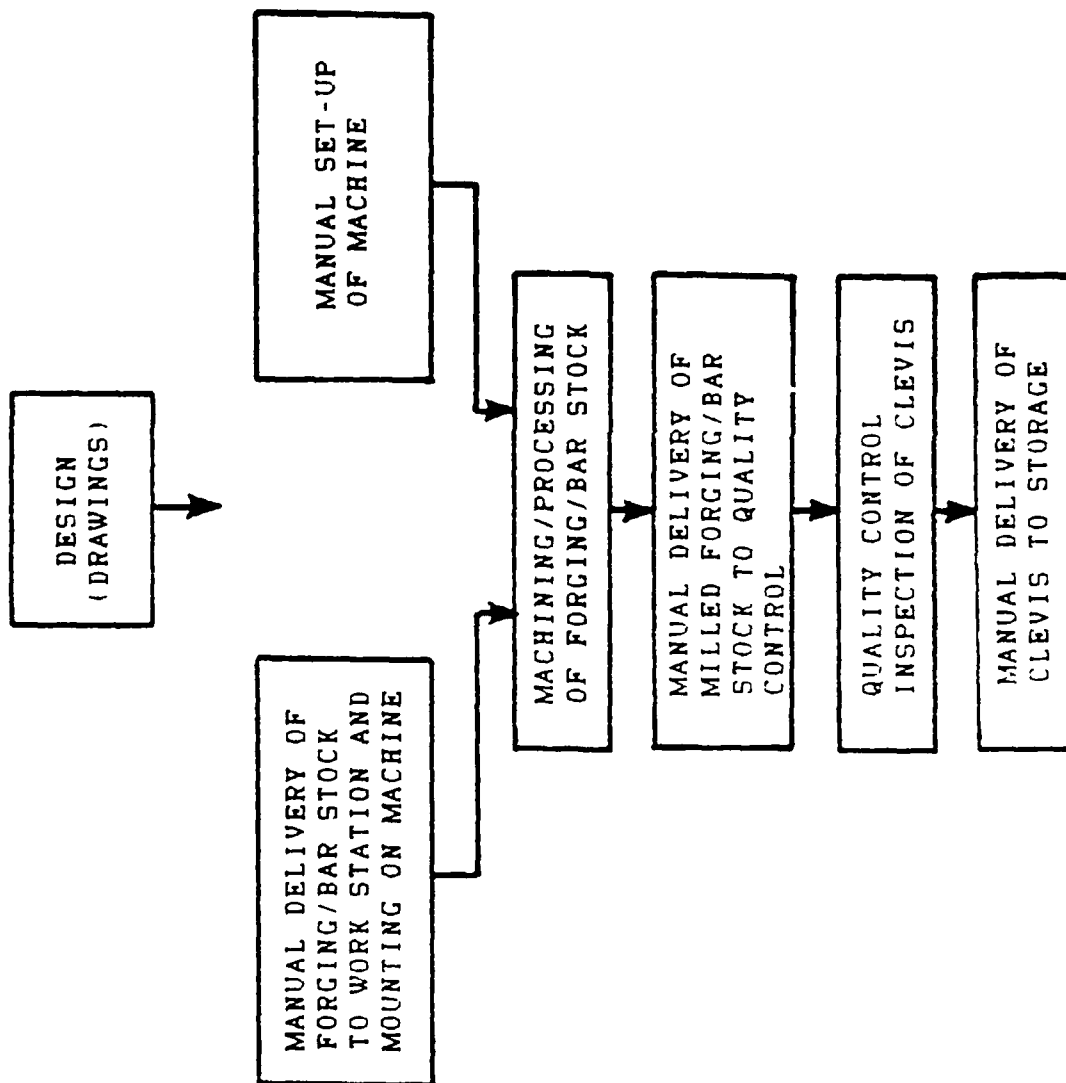Figure 1 Representative FSP: Drag Brace Rod End Clevis

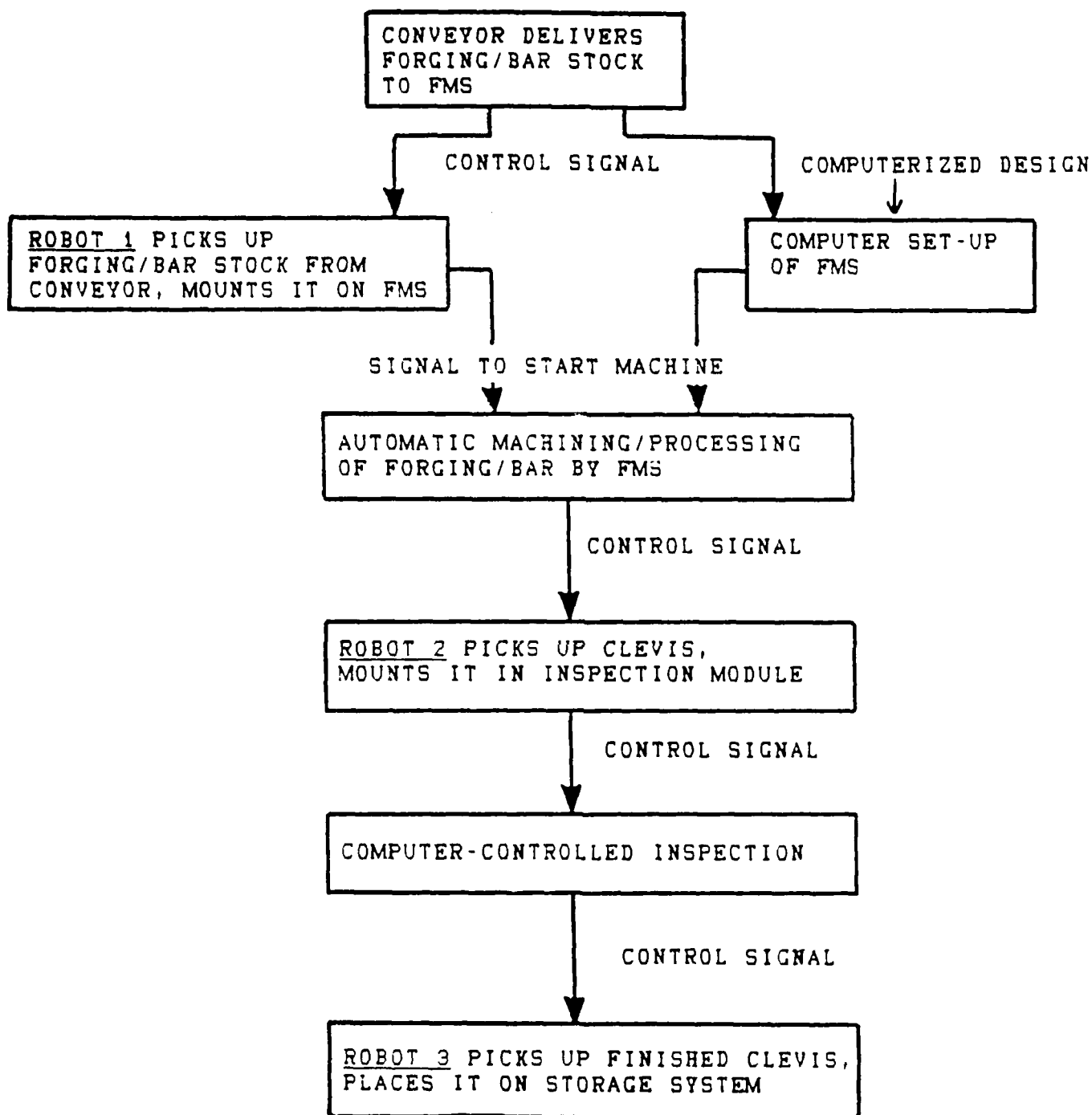129

Figure 2. Current Clevis Manufacturing Process

Figure 3  Clevis FMS Model (Conceptual)

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computer numerically controlled (CNC) machine tools which are used for manufacturing and modifying parts. These are listed in Table 2. As shown, the greatest concentration of these machines is in the manufacture machine shop, which is where the parts authorized for local manufacture are made; there are five mills and five lathes in this shop. The work in this shop is controlled by a manufacturing planning branch. Numerical control programming support is provided by a project design and development branch, which has extensive CAD/CAM systems. (This branch also does tool and fixture design.) Discussions with personnel in this branch regarding the feasibility of structuring an FMS at CCAD revealed that one minor problem may be that there are different programs on each different machine tool (since each has a different controller). However, they saw no difficulty in tying all the systems together through a central computer. A personal computer would have to be purchased to serve as the central computer. Standard fixturing and standard tooling would also have to be developed to accommodate an FMS; such development was estimated to be about a three man-month effort. In summary, then, there appear to be sufficient computer numerically controlled machines within a suitable area (the manufacture machine shop) with manufacturing planning, numerical control programming, and standard fixturing and tooling design support available at CCAD for the initial structuring of an FMS there.

Once one or more representative critically short flight safety parts have been identified as candidates for FMS, the processes required to manufacture the part(s) will be determined and compared to the CCAD resources available. From this information the detailed structuring of an FMS at CCAD will proceed.

The FMS model at CCAD will be validated by determining if the FMS structured will work and really solve the problem of critically short flight safety parts at CCAD and if candidate NDI methods for improving prevention of

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Table 2
Computer Numerically Controlled Machine Tools
Corpus Christi Army Depot

Manufacture Machine Shop:
    Monarch TC-1 Lathe (Allen-Bradley 7360 Controller)
    HES 400 Lathe (General Numerics GN6T-B Controller)
    HES 500 Lathe (General Numerics GN6T-B Controller)
    Hardinge SuperSlant 2-axis Lathe (Allen-Bradley 8200 Controller)
    Hardinge SuperSlant 4-axis Lathe (General Numerics GN6T-C Controller)
    Autonumerics MVC-10 Machining Center (Positool Model II CNC-M Controller)
    Monarch VMC-75 Machining Center (GE Mark Century 1050 Controller)
    Hitachi 614 4-Axis Machining Center (Fanuc 6M Model B Controller)
    Lagun Matic Milling Machine (Bendix Dynapath System 10 AM Controller)
    Cincinnati Bridgeport (Anilam Controller)
Turbine Engine Machine Shop #1
    Lagun Matic Milling Machine (Bendix Dynapath System 10 AM Controller)
Turbine Engine Machine Shop #2
    HES 400 Lathe (General Numerics GN6T-B Controller)
    K&T Milwaukee VB-4 Machining Center (Kearney & Trecker Gemini Controller)
Component Machine Shop
    Toyoda CNC Universal Grinder (Toyoda Grinder Control)
Structures Branch
    Whitney #636 Punch Press (Westinghouse Numerical Controller)
    Spectra-physics 5-Axis Laser (Allen-Bradley 8200 Controller)
    Weidemann Turret Punch Centrum 3000/Q (Fanuc OP Controller)
    Lagun Matic Milling Machine (Bendix Dynapath System 10 AM Controller) (2)
Equipment Manufacturing Section
    Hitachi H-CUT 304 Wire-cut EDM (Fanuc 6M Model H Controller)
    Hitachi 610 3-Axis Machining Center (Fanuc 6M Model B Controller)
    Mitsui Seiki 7CN Jig Bore (Fanuc System 11M Controller)
Other
    Gildemeister MD 5S Lathe (Gildemeister Electro Pilot M Controller)
    Mitsui Seiki 6GN Jig Bore (Fanuc System 11M Controller)
    GMF S-360 Robot Arm (Fanuc Controller) (for metal spray)
    Dabber Welber, Hobart (OM-452 Controller) (2)
    Paint Robot, Graco (OM-5000 Controller)
    CAD/CAM Unigraphics
    Plotter/Digitizer

corrosion during CCAD overhaul/NDI operations can be incorporated into the model. A further point of validation will be whether the FMS structured eliminates the barriers investigated. In the area of cost and economics, there will be consideration of whether it is worth the investment of CCAD and the Army in the FMS structured.

## 4.0 SUMMARY AND CONCLUSION

This report has given the results to date of a special investigation to develop an NDI oriented manufacturing model for CCAD into which can be incorporated NDI corrosion prevention methods. The emphasis has been on structuring a flexible manufacturing system (FMS) at CCAD.

FMS, in general, has been discussed, and the barriers to implementation of FMS have been described. The report has laid out the preliminary steps taken in structuring a flexible manufacturing system at Corpus Christi Army Depot and has indicated how the further structuring will proceed. Finally the report has described how the FMS model at CCAD will be validated.

It can be concluded, so far, from this special investigation that no significant obstacles exist to structuring an FMS and validating it.

# 10.0 ISSUES IN DEVELOPING AN NDI ORIENTED CCAD MANUFACTURING MODEL

# 10.0  ISSUES IN DEVELOPING AN NDI ORIENTED CCAD MANUFACTURING MODEL

**RTA**   **Reliability Technology Associates**
700 Ravinia Place
Orland Park, IL 60462-3750        October 24, 1988
(312) 349-9590


Dr. Frank A. Iddings
Director, NTIAC
Southwest Research Institute
Post Office Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Subject:  Issues in Developing an NDI Oriented CCAD Manufacturing Model
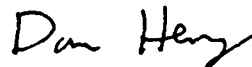
Reference:  SwRI Purchase Order No. 19359, Change Order No. 1, Item C

Dear Frank:

In the course of carrying out the reference program, several issues have arisen. These issues have been thoroughly discussed and resolved with Mr. Lewis Neri, who is monitoring this program for AVSCOM DERSO. A discussion of these issues is attached for your information. In previous documentation for the reference program, it has been pointed out that the emphases in the program have been on possible planning and control systems for overhaul/NDI operations at Corpus Christi Army Depot and on structuring a flexible manufacturing system for CCAD.
If you have any questions, please contact me at (312)349-9590.

Sincerely,

C. D. (Dan) Henry III
Program Manager


CDH/b

Attachment

# ISSUES IN DEVELOPING AN NDI ORIENTED
# CCAD MANUFACTURING MODEL

Issue Number 1.    The impact on scheduling of just-in-time (JIT), optimized production technology (OPT), and material requirements planning (MRP).

MRP systems generate a list of materials required to produce a specific number of output units; this in turn generates purchase orders and production orders. Large quantity factors (called scrap factors) are often inserted to generate excess needed materials at the purchasing end. This is referred to as a "push" system.

In JIT systems, which are "pull" systems, materials are not fed into the production cycle until finished product is actually required. Product requirements, not forecasts, trigger production. This requires very short lead times.

In OPT production is scheduled on a "bottleneck" basis. Bottleneck areas in a facility are analyzed and emphasized. Production is planned so that bottleneck work centers are utilized to the maximum and nonbottleneck work centers keep the bottleneck work centers working at full production all the time.

MRP sequences tasks as if the plant has infinite resources available and then adjusts the schedules by adding a capacity requirements planning step; this two-step procedure is not as efficient as developing optimal schedules in one step. Both JIT and OPT schedule production assuming limited capacity. Kanban cards control capacity in JIT; bottlenecks, in OPT. OPT allows more variable constraints than MRP and merges MRP and capacity requirements planning functions into one tool.

MRP systems assume that a part passes all stages of production in a fixed-sized batch. Batch size is kept larger than necessary in order to offset costs incurred by large setup times. A reduced setup cost is allocated

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per part. Increased batch sizes increase product lead time, which increases interest and storage costs which, in turn, translate into increased overall cost.

In JIT all setup times are reduced to a minimum so that it will not be a significant factor in determining batch sizes; batch sizes can then be kept small.

In OPT variable batch sizes are computed. Setup time is reduced to a minimum in bottleneck work centers, maximizing output in these areas and of the whole facility.

Production waves in an MRP system are balanced through use of safety stock. In JIT, the entire production sequence is forced to stay in synchronization and production waves are not allowed to occur. In OPT, production waves are prevented by tighter scheduling and through the use of safety capacity.

OPT supplies a more complete schedule than JIT; however, JIT supplies it faster. OPT's time performance in developing schedules is faster than MRP.

JIT is the most flexible because of its minimal batch sizes and low inventory levels. OPT schedules lower levels of inventory and allows for flexible batch sizes and, thus, allows for more flexibility in production than MRP.

JIT generally requires a total reorganization of the facility; OPT offers much of the same flexibility without a reorganization. OPT can be phased into an operation, so the entire facility is not necessarily affected by installation of an OPT system. OPT allows for parallel operation with an MRP system so the proper operation of an OPT system can be assured.

MRP has a number of shortcomings, including rigid lot-sizing rules, rigid average queue times, an inability to split lots or send ahead partial lots, sequential (rather than simultaneous) date setting and capacity requirements calculations, iterative load balancing to eliminate overloads,

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and a lack of finite scheduling logic.

In terms of OPT, it appears that the OPT production planning and inventory control technique has an improved ability for production planning, compared to MRP.

OPT has a simplified technique for production scheduling, compared to MRP. Schedules are not as time-consuming to set up. Schedules do not require as much data. Less accuracy is required in the data. Less computer processing capability is required. Less people time is required to analyze the schedule.

The user portion of OPT is less complex than that of MRP. The internal mathematical technique contains additional sophistication that makes the system user's job easier. Less user knowledge is required.

OPT gives a more rapid projection of schedule, compared to MRP. These quicker schedules allow quicker modifications of the schedules and therefore more flexibility in the schedules. Schedules changes can occur in a few hours rather than days. Quicker schedule development allows simulation to be used in the scheduling process.

OPT analyzes plant production, which MRP does not do. Bottlenecks in the production process are specifically defined, so improvements are easily made on the bottlenecks. Simulation can be used to test variations in plant output and how this effects plant load. Capacity planning can be simulated in OPT.

In addition, actual finite manufacturing resources are taken into account in OPT. OPT simultaneously maximizes production output and minimizes work-in-progress inventory as a basis of the optimization in the OPT mathematical technique. Therefore, increased production output, using the same resources, and reduced work-in-progress inventory are possible with OPT. Smaller batch sizes are calculated based on profitability in OPT rather than from a set formula in MRP; MRP has rigid lot-sizing rules. Finally, the OPT scheduling system allows for finite control of the resources on the short

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term.

On the other hand, OPT requires a facility reorganization, including a conceptual reorganization, replacement of data processing systems, a changed management style, new reporting systems, and equipment changes and movement. Costing and accounting systems will be disrupted by OPT because efficiency

can no longer be calculated, job cost control data have been restricted in some areas, and performance evaluations no longer exist. Users will be disrupted and will need to be retrained; new reports will need to be developed for data processing and accounting to handle the new information base. In addition, OPT produces a tighter schedule, allowing less ability to accommodate production errors. Also, the financial analysis systems need to be changed to accommodate the OPT philosophy.

OPT can be compared to JIT in several areas. Both OPT and JIT are geared to reducing inventories and identifying bottlenecks. OPT is a computerized system while JIT is manual. With OPT, then, bottlenecks and the impact of alternate approaches can be analyzed in advance without creating problems on the factory floor. The use of workers, materials, and machines is optimized to maximize the utilization of critical resources, maximize plant output and minimize work-in-process inventory and manufacturing times. OPT can also be used more universally than JIT which is applicable only in repetitive manufacturing with fairly stable demand. OPT can also be used in job shop and process industries. A key difference between OPT and JIT is that JIT maintains a logistical chain between operations while OPT has a logical one.

In conclusion, then, theoretically and technically, each system appears to be sound in its own way and should be able to accomplish low-cost, high-quality, on-time production. Both JIT and OPT seem to be more productive than MRP, and OPT is seen as more complete than JIT in that it includes many features of JIT and additional benefits as well.

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Issue Number 2.    The influence of the above systems on the installation of a
                   flexible manufacturing system.


     Flexible manufacturing makes "just-in-time" manufacture and delivery
feasible so that inventory costs can be greatly reduced, but allows instant
response to customer needs.  With an installation of a flexible manufacturing
system a schedule of material delivery can be set up that cuts down on
materials inventory.  By using a flexible manufacturing system with proper
scheduling of production, waiting time of a part for a given machine is
reduced, reducing queue sizes and reducing the necessary floor space for
waiting lines.


     Flexible manufacturing systems can incorporate planning and control of
their machinery operations within their computerized integrated-control data
systems.  These data systems can have built-in production planning routines;
system parts-programming routines; materials-handling routines for parts,
tools, and accessories; and stock control in the form of separate modules.
Parts programming and scheduling may, in turn, include subroutines like
alternative routing of batches, statistical quality monitoring and control,
and balancing of assembly tasks among individual flexible manufacturing
stations.


     Once management selects performance criteria and defines limitations and
work rules for flexible manufacturing systems, the computerized
integrated-control systems can take over and prioritize and schedule
individual orders (production batches) in a near-optimum manner.  The
integrated-control systems can regulate the times when machines operate and
the flow of parts.  A flexible manufacturing system, therefore, does not need
any of the other operations planning and control systems, such as MRP, JIT, or
OPT.  It can have planning and control built into its machinery controls
themselves.

Issue Number 3. The differences between traditional manufacturing and flexible manufacturing.

Traditionally, a manufacturing process has been dedicated to a single product. Adapting to changing requirements for products and systems in traditional manufacturing requires major retooling and down times while flexible manufacturing allows continuous incremental adaptation quickly to changing needs.

When a traditional manufacturing process receives a small order, less than the economic lot size, the manufacturer schedules a production run of the part and produces the economic lot size. He ships the number ordered and puts the rest into inventory with the hope that he will receive further orders for the part. With a flexible manufacturing system the exact number of parts ordered is scheduled with no excess parts going into inventory. Thus, inventory cost is reduced, both in terms of raw material and in terms of finished products, with flexible manufacturing as compared to traditional manufacturing. Lead time is also reduced from the order of a month in traditional manufacturing plants to a few days in flexible manufacturing systems. Lead time is defined as net processing time plus waiting time (in buffer storage, at machines, and during transport between machines); in a traditional manufacturing environment it is not unusual for waiting time to be as much as one thousand times longer than net processing time. The flexibility and faster responsiveness encourages smaller factories closer to their markets with flexible manufacturing than with traditional manufacturing.

Flexible manufacturing systems require substantially less floor space than traditional manufacturing machinery. Savings in floor space are obtained from the machines themselves as well as, due to reduced inventory, from smaller warehouses for raw materials, intermediate goods and finished goods.

Compared with traditional manufacturing systems, a flexible manufacturing system requires more training of personnel, both immediately following the decision to invest in a flexible manufacturing system and continuously over the lifetime of the flexible manufacturing system.

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Even though flexible manufacturing systems include sophisticated diagnostic subsystems, total maintenance costs increase when compared to traditional manufacturing systems. The complexity of flexible manufacturing systems as well as the consequences of a possible breakdown necessitate more extensive preventive maintenance programs than are needed for traditional manufacturing systems.

In traditional manufacturing up-front capital investment is needed while market demand is being built; flexible manufacturing allows rapid and low-cost state of the art manufacturing of new products while demand is being built without the need for up-front capital investment.

Issue Number 4.   Barriers to the installation of flexible manufacturing systems and how they are removed

There are several barriers to the installation of flexible manufacturing systems. The source of most of the barriers is integration. Many of the advantages of flexible manufacturing, its reduction of lead time, its predictability of operation, its consistency of results, derive from its integration and automation of multiple elements into a complete system. However, the dominant management and organizational theories employed in traditional manufacturing are centered around specialization and division of labor.

To achieve the integration required, the traditional manufacturing infrastructure may have to be altered since it has most probably been designed to support specialization as opposed to integration. Establishing the infrastructure needed to support the installation of a flexible manufacturing system will be as important in removing barriers to installation as understanding the technology of flexible manufacturing systems. Installation of a flexible manufacturing system blurs lines and creates overlap between departments. It changes job descriptions. It demands that employees understand the challenges faced by fellow employees in other functional areas. Management must integrate the efforts of each of its departments. All elements of the organization must be integrated in cross discipline management teams for the installation of a flexible manufacturing system to be most

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effective.

The installation of a flexible manufacturing system then should lead to the restructuring of the organization so as to optimize the capability of the system. This restructuring should reduce the number of management levels to a minimum in order to make the organization as responsive to the market as possible and to take maximum advantage of the flexibility of the flexible manufacturing system. Reducing the number of management levels will speed the flow of information from shop floor to top management and in the opposite direction, from top management to shop floor. Not only will the information flow be speeded up, but the quality of the information will be improved resulting in more efficient and effective operation.

To achieve the necessary integration, there may also have to be greater cooperation among groups within the manufacturing environment; for example, the manufacturing and engineering groups that have rarely needed each other in the past may be required to work hand-in-hand. To facilitate cooperation, performance measures or some form of incentive may be required.

Organizational spirit is a principal determinant of whether the integration needed for the successful installation of a flexible manufacturing system can be achieved. There must be compatibility between the technology and the organization into which it is to fit. There must be rationality in organizational decision making, understanding of the technology and the organization into which it is to fit, appropriate matching of technology to organizational strengths and weaknesses, and suitable infrastructures to support the flexible manufacturing systems. Sometimes rigid rules perpetuate traditional manufacturing approaches and represent a significant barrier to successful integration.

To achieve the proper organizational spirit for installation of a flexible manufacturing system, top management must, first, determine and prioritize organizational objectives as they relate to operations (cost, quality, delivery, flexibility, positive work environment, increased employee involvement); the organization needs to clearly understand the reason it is installing a flexible manufacturing system and how it will be used.

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Management must continually emphasize these priorities through actions as well as words. To support installation of a flexible manufacturing system, adequate changes must be made in performance measures and necessary resources must be made available. Second, top management must determine a specific plan for installation of flexible manufacturing systems which will serve as a road map for the installation. Management must also determine and implement the specific changes necessary to support the plan. Third, management must communicate to all employees the reasons for installation of a flexible manufacturing system. Such communications may include a brief history of the events leading up to the installation, a current state of the business and why installation of the flexible manufacturing system is required now, and what changes need to be made. A uniform tone should be set regarding what needs to be done. Everyone should be informed as to the who, what, where, when, how, and why concerning the installation of the flexible manufacturing system. Fourth, performance measures must adequately reflect the positive effects of the installation of the flexible manufacturing system and provide incentives for managers to support the installation.

Software integration is another barrier to the installation of flexible manufacturing systems. The three types of software (business - accounting, production scheduling; manufacturing - route sheets, machining instructions; and engineering - bills of materials, drawings (CAD/CAM)) need to be able to communicate with each other: the facility's production and scheduling system has to interface with the flexible manufacturing system scheduling system and the flexible manufacturing system has to interface with engineering. There are challenges in obtaining software, debugging it, interfacing it, maintaining (updating) it, and solving compatibility problems between the different conventions used in the systems.

Another integration-related barrier is the pressure flexible manufacturing systems place on interfacing systems, both internal subsystems and external systems.

The entire flexible manufacturing system must be optimized, not each individual internal subsystem. It must be recognized that each machine no longer performs independently on its own. In flexible manufacturing systems

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inefficiencies such as appreciable downtime cannot be tolerated since problems in one stage of the process immediately affect the performance of the entire system. The ramifications of a machine breakdown are far-reaching because many times in a flexible manufacturing system there is no way to compensate for it and the entire system may be down until a single machine can be gotten up and running. The difficulty in providing adequate maintenance to prevent machine breakdowns is a barrier to the installation of flexible manufacturing systems.

Flexible manufacturing systems also place pressure on external systems interfacing with them, both within the plant itself and outside the plant, such as subcontractors and other vendors. Inventory reductions and changes in product quality can add to the cost and schedule problems of external interfacing systems. If drastically shortened lead times are to occur with flexible manufacturing systems, then these interfacing systems must also be ready to move to shortened lead times. Subcontractors and other vendors must be warned sufficiently in advance and helped to prepare for the change. Installation must be carefully planned to take this into account.

Human considerations represent the biggest barrier to installation of flexible manufacturing systems; they can severely constrain how fast the installation of a flexible manufacturing system can occur and must be considered at the earliest stages of installation planning to assure peak performance from the system. One aspect of this issue is the resistance to change due to the inertia and familiarity of old procedures and conventional methods of operation; either management or labor groups may perceive the flexible manufacturing system as a direct threat. The restructuring discussed previously can be very traumatic to the persons involved. This resistance to change is sometimes grossly underestimated. However, the formal and informal reward and incentive systems, if changed to suit the flexible manufacturing technology, can help to minimize this resistance. If not changed, both custom, as well as the formal and informal reward and incentive systems, may work against installation of flexible manufacturing systems. Taking steps to help the team absorb the technology of flexible manufacturing systems is as important as understanding the technology itself in removing barriers to installation of a flexible manufacturing system.

Management must recognize that new organizational structures may be necessary that allow more employee participation in design and planning, as well as in some decision-making processes. Managers and engineers will need more finely honed human management/interaction skills to provide necessary motivation and enthusiasm and inspire employee cooperation.

Another aspect of human considerations, a major barrier to the installation of flexible manufacturing systems, is the shortage of suitable manpower. There is a serious shortage not only of engineers, but also of technicians and craftsmen. American industry generally gives low priority to manufacturing; much more money is spent on new product development than on process innovation. There is a shortage, then, of young manufacturing engineers. In addition, typical organizational structures do not encourage long-term technical careers; the top of the technical ladder is generally reached by an engineer in only five to seven years. To progress further in the organization, a talented engineer must move into management. To get the best talent to go into manufacturing related fields, organizations need to place new emphasis on manufacturing and put in place a career path which recognizes and rewards the technically minded individual.

The difficulty of providing proper training for people is another barrier to installation of flexible manufacturing systems. Organizations must devote sufficient resources to the development of the planning, analysis and design skills that will be needed for the successful installation of flexible manufacturing systems. Education, in all forms, may constitute a good 90% of the total effort involved in installation of a flexible manufacturing system. A comprehensive training program must be instituted to meet the need for well trained workers familiar with the principles of automation, computer technologies, and manufacturing processes.

In addition, the work environment may have to be changed to enhance the man/machine interface.

A significant technical barrier to the installation of flexible manufacturing systems, especially untended systems, is the general lack, at

this time, of tooling automation. Automation is needed in tool transport and changing, tool identification and recognition, tool monitoring, tool storage, and tool management. Methods designed for tooling automation in flexible manufacturing systems are being developed. The transporting and exchanging of cutting tools can be performed by automatic guided vehicles, overhead transport carriers or rail-guided carts. Bar codes and memory chips are two means of tool identification under development. Adaptive control and various sensors can monitor tools for wear and breakage. All of these modes of automation under development require a sophisticated computerized tool management system. The powerful computers, relying on extensive data-bases, that monitor and control the flexible manufacturing system can include this tool management.

Another barrier to the installation of flexible manufacturing systems is that management accounting systems have failed to keep pace with recent manufacturing technology like flexible manufacturing systems. Planning and accounting systems as they are currently used are inadequate in the justification of flexible manufacturing systems. Flexible manufacturing technology enables a flexible manufacturing system to have a very long useful life because of its adaptability to product changes in response to the market. Thus, new machines or major modification of current machines are not needed to respond to product changes. Thus, in order to properly develop a financial justification for flexible manufacturing the time frame must be long enough to capture all the benefits. The planning horizon used in justification, in most cases, is too short to recover all of the benefits associated with a flexible manufacturing system and does not take into account the extended useful life of the equipment. Because of the high initial capital costs a flexible manufacturing capability cannot be justified in a short term financial analysis.

In order to remove the barriers to installation of a flexible manufacturing systems the following steps should be followed in the installation. First, a clear understanding of what the flexible manufacturing system can do and how it will satisfy a need that exists should be obtained. Second, adequate resources should be assigned to analyze the system and the application in adequate detail to create a detailed functional specification.

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Third, a strong relationship should be developed with appropriate suppliers to obtain a common understanding of the problem as well as the criteria for an successful installation. Fourth, users should be involved up front to gain understanding and take ownership by having them participate in the design and setting up visits for them to system vendors; groundwork should be laid for any union negotiations by explaining reasons for contract changes needed. Fifth, proper training should be provided to all stakeholders in the installation project, including management and supervisors as well as individual operators. Sixth, proper resources should be allocated to support the flexible manufacturing system once it is in place; this includes properly trained operators and skilled, knowledgeable technical resource personnel.

In summary, the real barrier to installation of a flexible manufacturing system is not the technical change itself, but the human changes that must accompany the installation. Helping people adapt to change is a key ingredient in removing barriers to installation of flexible manufacturing systems. The human considerations that must be addressed include the amount of integration required between departments and between management layers, the perspectives and skills required to perform tasks in a new way, and the level of understanding that is needed to successfully maintain and operate a flexible manufacturing system.

Issue Number 5.  Verification and quantification of the benefits from flexible manufacturing systems for use in justifying the installation.

The issue of whether to use flexible manufacturing and the justification of its use is a very complex one. The technology is new and in a continual state of development, which makes it difficult for the decision maker to remain technically current. In addition, the cost effects of flexible manufacturing systems are difficult to identify and calculate. Many of the indirect costs associated with manufacturing systems, in general, are hidden in the over-all costs of production. What is needed is the development of cost and accounting systems that break down input costs, not only by product levels but also by production process levels for each product category. Such accounting systems would provide an important tool for verifying and

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quantifying the benefits of flexible manufacturing. The measurements applied by management are as important as the technology itself in justifying the installation of a flexible manufacturing system.

Some benefits from flexible manufacturing systems can be quantified as follows.

The benefit of flexibility can be quantified in terms of batch setup times, the degree of effort needed to change production schedules, the operational envelope, and the number of different operations that can be performed. An index of flexibility can be established.

Quantifying the cost benefit of flexibility is difficult. Some benefits can be credited in the calculated savings resulting from lower capital cost of inventory. However, this does not take fully into account the flexibility benefits. A possible approach would be to extend the economic lifetime of the project, compared with the practice followed for other investment objects. This would lead to lower annual average capital costs for the flexible manufacturing system.

The benefit of variability of product type can be quantified by determining the number of different product families and the number of variations within each family that are produced by the system.

The benefit of increased system utilization can be quantified by considering the unit direct costs associated with products and indirect costs. As system utilization goes up, unit product costs will generally go down, but overall indirect costs associated with plant operation will go up. If all costs are distributed to the product, then as utilization goes up, the per product cost will drop.

The benefit of reduced inventory costs can be considered in three categories: material inventory, work-in-process inventory, and product inventory. The benefit of reduced material inventory costs can be quantified by considering the reduced capital invested in the materials and the cost of space to store the materials. The benefit of reduced work-in-process

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inventory costs can be quantified by considering the reduced labor costs due to shortened production time and the reduced overhead associated with floor space. (Work-in-process inventory reduction can also be evaluated by measuring reduced lead time.) The benefit of reduced product inventory costs can be quantified by considering the reduced capital invested in parts inventory and the reduced cost of storage (space and labor).

Justifying the installation of flexible manufacturing systems based on verification and quantification of benefits, in general, is made difficult by the fact that approaches used in justifying the installation of traditional equipment are ill-suited to flexible manufacturing systems. These approaches are based, implicitly, on several assumptions regarding the equipment. It is assumed that the benefits of the equipment are relatively narrow; that the capabilities of the equipment and technology are well known and unlikely to change after installation except, eventually, to decline; that the benefits can be estimated with reasonable accuracy; and that the benefits of the project under consideration can best be evaluated by the manager or the specialists most directly concerned with the project. These assumptions are not valid for installation of flexible manufacturing system hardware or software. A new set of installation justification measures needs to be developed.

The traditional approaches assume that the benefits are narrow. Flexible manufacturing systems, however, provide the basis for increasing the integration of the various stages of the manufacturing process. The benefits come from linking mechanical processes with inspection and material handling. especially for complex parts which have a high value added during the mechanical processes. In addition, flexible manufacturing systems assist in reducing both direct labor and indirect labor (e.g., in-process inspection, work tracking, transportation, tool control scheduling, production control). The smaller work teams that result from flexible manufacturing system installation tend to be more highly motivated and require less supervision.

The traditional approaches also assume that the capabilities of the equipment are well known and fixed (or declining slowly over time). This does not apply to most flexible manufacturing system installations. The

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contributions of true flexible manufacturing systems are likely to keep increasing for extended periods beyond initial installation. Users gain increasing understanding and experience over time. Rapid progress in hardware and software leads to equipment or even whole systems becoming upward compatible; they can be upgraded in steps. An intrinsic flexibility of flexible manufacturing systems is achieved through the ability of the system to acquire production capability incrementally, to simultaneously process many types of parts, and to convert production capacity.

Whereas the benefits of traditional equipment are quantifiable with reasonable accuracy, the benefits of a flexible manufacturing system installation are more difficult to quantify. Such significant benefits as better handling of engineering changes or reductions in lead time are unquantifiable. Yet these qualitative benefits often provide the justification for installation of flexible manufacturing systems.

The best person to suggest and evaluate flexible manufacturing system installation may no longer be the manager directly concerned with the application. A broader team is needed to evaluate flexible manufacturing systems.

Approaches for justifying the installation of flexible manufacturing systems must take into account the total flexible manufacturing system picture – the direct and indirect costs and strategic benefits of the proposed installation. All inputs should be included in the installation justification model; this may mean that hypothetical cost values may have to be attached to a given qualitative benefit. Quantification of benefits should cover a five to ten year horizon to take into account the longer-term impact of the installation of a flexible manufacturing system. Probabilities should be attached to the quantifications to account for the uncertainties inherent in any engineering or manufacturing project.

Accounting standards must be applied to a flexible manufacturing system carefully in order to truly reflect its benefits. This is especially important in the allocation of indirect costs to the product. In traditional manufacturing processes indirect costs are allocated to individual product

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units on the basis of direct labor hours. Since installation of a flexible manufacturing system reduces direct labor hours per product unit, but increases indirect costs, the allocation of indirect costs by direct labor hours is not realistic. Thus, accounting systems based on direct labor are obsolete since labor input may be small, 5 percent or even much less of total costs. The direct labor that is used is more concerned with set-up and supervision than with actual processing of output.

More imagination is needed for tracing costs to products which inevitably will require new and multiple overhead allocation bases. Costs associated with materials (purchasing, traffic, receiving, distribution, and storage) can be traced to materials purchases based on material dollars or on quantity, size, or weight of materials. Costs associated with acquisition, maintenance, repair, and operation of machines can be traced to products on a machine-hour basis. Costs of production control and expediting can be traced to product assurance, and customer support and service can be traced to the products which require or which benefit from them. Since materials, equipment, and overhead are the most important manufacturing costs, cost accounting systems that trace these costs to products rather than rely on arbitrary allocations based on direct labor must be developed.

Faster financial reporting is needed. In a flexible manufacturing system the primary variable costs are material, energy, and maintenance and repair of machines. The benefits from flexible manufacturing systems are long term since flexibility extends useful life beyond normal life cycles.

The accounting system must taken into account improved product quality, shorter lead times, reduced prototype costs, improved production flexibility, and reduction in downtime.

It is necessary, then, to expand procedures for justifying installation of flexible manufacturing systems. Current procedures emphasize the easily quantified benefits of reduced labor, materials, or energy. These benefits tend to be recognized for arbitrarily truncated periods, sometimes only one or two years. Neither of these assumptions is valid or helpful when contemplating installation of flexible manufacturing systems. While flexible

manufacturing systems offer significant direct labor savings, there are also considerable improvements in quality, inventory, and floor space reduction, great reductions in throughput and lead times, and flexibility to accomodate product redesigns and new generations of products; to consider only easily quantifiable labor savings significantly understates the benefits of flexible manufacturing system installation. The benefits from flexible manufacturing system installation persist over long periods. It is unlikely that the hardware and software investments in the system can be repaid in a couple years, but the flexibility of the technology ensures that the useful economic life will be much longer than that of traditional dedicated equipment. Procedures for justifying installation of a flexible manufacturing system must use realistic quantification of the considerable useful economic life of the system.

Issue Number 6.    Measurement of quality in flexible manufacturing systems.

Quality can be measured in several ways. Higher product quality leads to a reduction in the number of defective parts and products being manufactured. A defective part gives rise to losses corresponding to the value added to the part, to the cost of rework and scrappage, and to the resulting increased work-in-process inventory cost. The later in the manufacturing process the defect arises, the greater the loss - a loss whose value must be added to overall production costs and to the price of the output of non-defective goods. With higher product quality there is also a reduction in material overhead and other indirect costs related to materials. If a part or product becomes defective in the course of the manufacturing process, it has to be replaced. Besides leading to additional costs for the administrative work involved, this also causes disruption in the production process.

Defective parts also give rise to late deliveries to customers and to delays in cash inflow, as well as to a loss in customer goodwill - losses which are even higher in cases where the defective products are not detected before being shipped. A quality product will generate a larger market share and reduced warranty and repair costs of products sold.

Improved quality can be measured then by the increased revenues due to

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increased sales, the reduced material cost due to decreases in scrappage, the reduced labor cost due to decreases in rework, and the reduced warranty and service costs.

Measures of quality, then, are internal and external failure rates, yields, and rework.

# 11.0 QUANTIFICATION OF ARMY AIRCRAFT CORROSION CONTROL FAULT TREE

# 11.0 QUANTIFICATION OF ARMY AIRCRAFT CORROSION CONTROL FAULT TREE

**RTA**    **Reliability Technology Associates**
700 Ravinia Place
Orland Park, IL 60462-3750
(312) 349-9590        November 21, 1988


Dr. Frank A. Iddings
Director, NTIAC
Southwest Research Institute
Post Office Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Subject:   Report: "Quantification of Army Aircraft Corrosion Control Fault
            Tree"
         SwRI Purchase Order No. 19359

Reference: Letter Report: "A Fault Tree Approach to Corrosion Control for
                   Army Aircraft", October 18, 1988

Dear Frank:

This report presents the results of a quantification of the fault tree
concept approach outlined in the reference previous report. Computational
techniques were used to analyze the basic faults, determine failure mode
probabilities, and establish criticalities, utilizing basic fault data and
failure probabilities, in order to identify and rank critical faults. The
fully implemented quantified fault tree concept approach will greatly
facilitate the planning, specification, and implementation of Army aircraft
corrosion control.

Several steps were taken in implementing the quantification.

First, fault tree identification numbers were assigned to the basic
faults of the fault tree diagram. The identification number is a two number
designation, with the numbers separated by a dash ("-"). The first element is
the figure number and the second is the number of the basic fault within that
figure. For example, basic fault 2-4 is the fourth basic fault in Figure 2.
The numbers are assigned from left to right, beginning at the top of the fault
tree and working down. Figures 1 through 4 show the corrosion-related fault
tree presented in the reference previous report with the identification
numbers assigned to each basic fault.

Second, data on the probability of occurrence were compiled for each
basic fault identified in the fault tree. Data for each basic fault on the
corrosion-related fault tree can be derived from either human error
probability data or manufacturing process defect data. Human error
probability data were taken from NUREG/CR-1278-F, "Handbook of Human
Reliability Analysis with Emphasis on Nuclear Power Plant Applications",
Sandia National Laboratories, August 1983. For manufacturing process defects
an acceptable quality level of 2.5% was assumed. The fault probability,
$P(X_i)$, for each basic fault on the corrosion-related fault tree is given in
Table 1.

Third, the conditional probability, $P(I/X_i)$, of each basic fault was computed. Conditional probability is the probability that an occurrence of a basic fault will cause component failure due to corrosion. Conditional probabilities are computed by assigning a fault probability of 1.0 to a basic fault and then determining the resultant probability of component failure due to corrosion. This involves computing the occurrence probabilities for all events, as well as component failure due to corrosion, based on the combinatorial properties of the logic elements in the fault tree. The analysis involves repeated applications of basic probability expressions for the fault tree logic gates. Given a fault tree consisting of basic faults and interconnected output events, the output event probabilities are computed, starting with the lowest levels and continuing to the highest levels in the tree. The computations for the logic gates are given by:

"And" Gate

$$P(F) = \prod_{i=1}^{n} P(I_i)$$

"Or" Gate

$$P(F) = 1 - \prod_{i=1}^{n} (1-P(I_i))$$

where: $P(F)$ is the output probability,
$P(I_i)$ is the probability of the ith input, and
$n$ is the number of inputs.

"Inhibit" Gate - Each "inhibit" gate was considered to satisfy the respective enable condition (i.e., to have a probability of 1.0)

The conditional probability of each basic fault on the corrosion-related fault tree is given in Table 1.

Fourth, the criticality of each basic fault was computed. Criticality is a measure of the relative seriousness or impact of each fault on component failure due to corrosion. It involves both qualititative engineering evaluation and quantitative analysis and serves to provide a basis for ranking the faults in their order of severity. The objective is to assign a criticality numeric to each basic fault based on its occurrence probability and its conditional probability. Criticality can be defined quantitatively by the following expression:

$$CR_i = P(X_i) \times P(I/X_i).$$

The criticality of each basic fault on the corrosion-related fault tree is given in Table 1.

Fifth, the criticalities for all basic faults were ranked in descending order, i.e., the most critical basic fault was assigned to position 1, while the least critical basic fault was assigned to the last position. Associated with each ranked criticality value is a cumulative sum of all previously ranked criticalities. For example, the cumulative criticality for the third

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ranking basic fault is the sum of the criticalities for ranked basic faults 1, 2, and 3. The rank order and cumulative criticality for each basic fault are shown in Table 2.

Finally, the cumulative criticality as a function of criticality ranking was plotted to produce the relative criticality curve shown in Figure 5. The curve can be divided into three distinct regions of criticality: the most critical region, the marginally critical region, and the non-critical region. The position of each basic fault on the graph is identified in Table 2.

This criticality data should be reviewed by Southwest Research Institute to identify priority areas for engineering investigation in Tasks 2 and 3 and Task 3/Mod. 2 of the NDI oriented corrosion control program for Army aircraft, Phase I Inspection Methods, and to show quantitatively the impact on component failure due to corrosion of various NDI corrosion detection techniques, corrosion detection criteria and guidelines, and candidate NDI corrosion prevention methods.

If you have any questions on this, please contact me at (312) 349-9590.

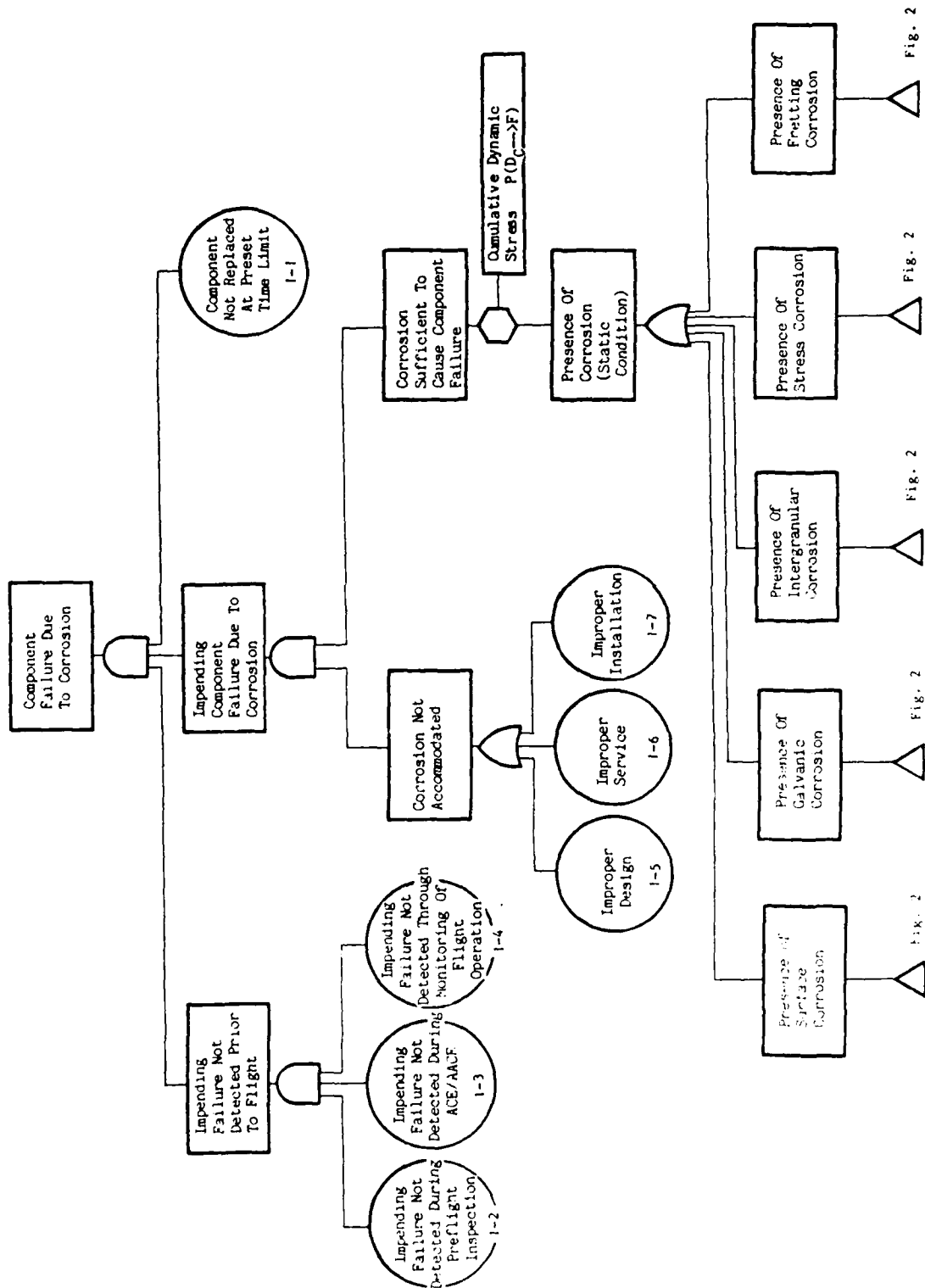Sincerely,

Dan Henry

C. D. (Dan) Henry III
Program Manager

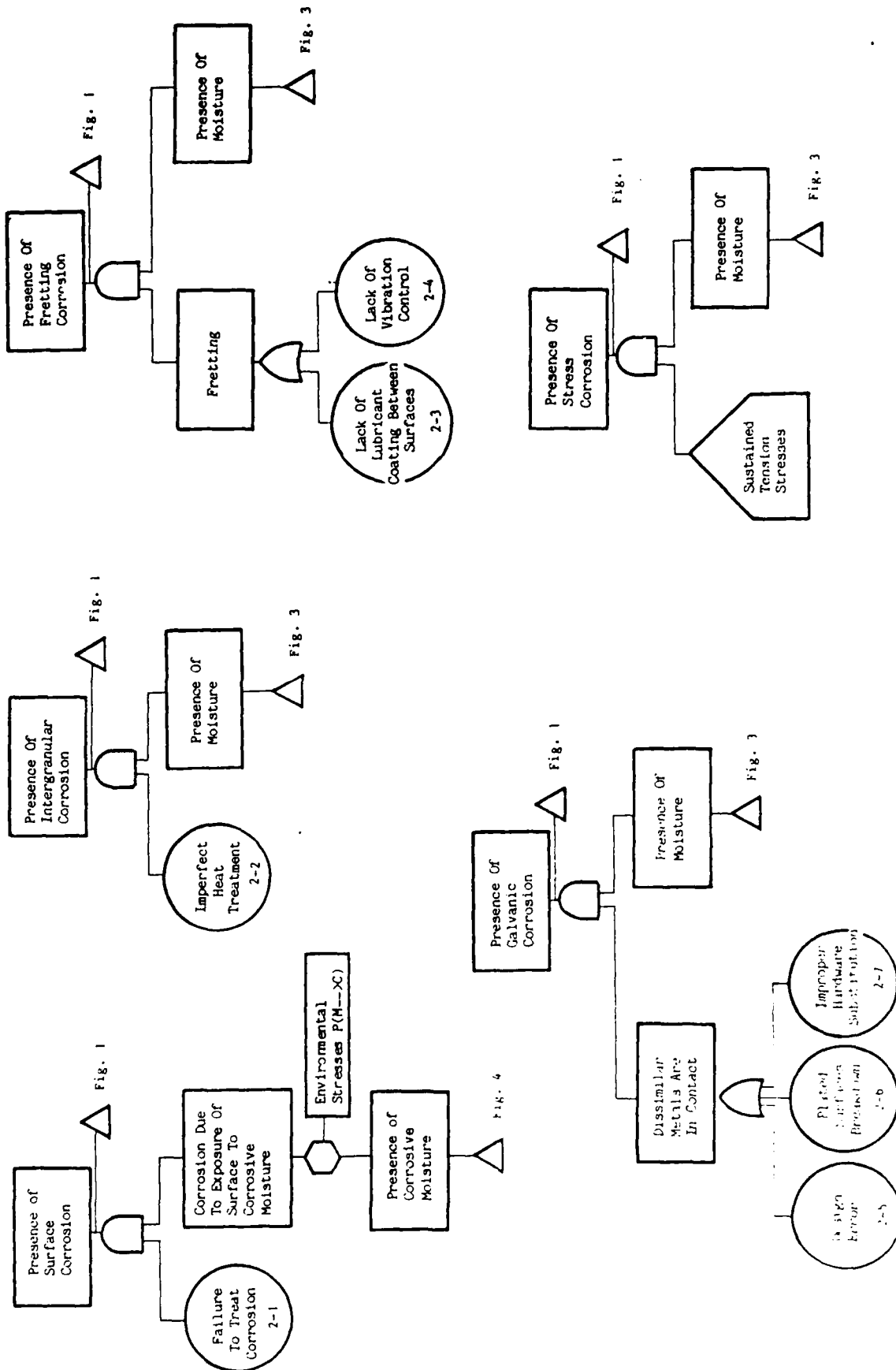Figure 1   Corrosion-Related Fault Tree
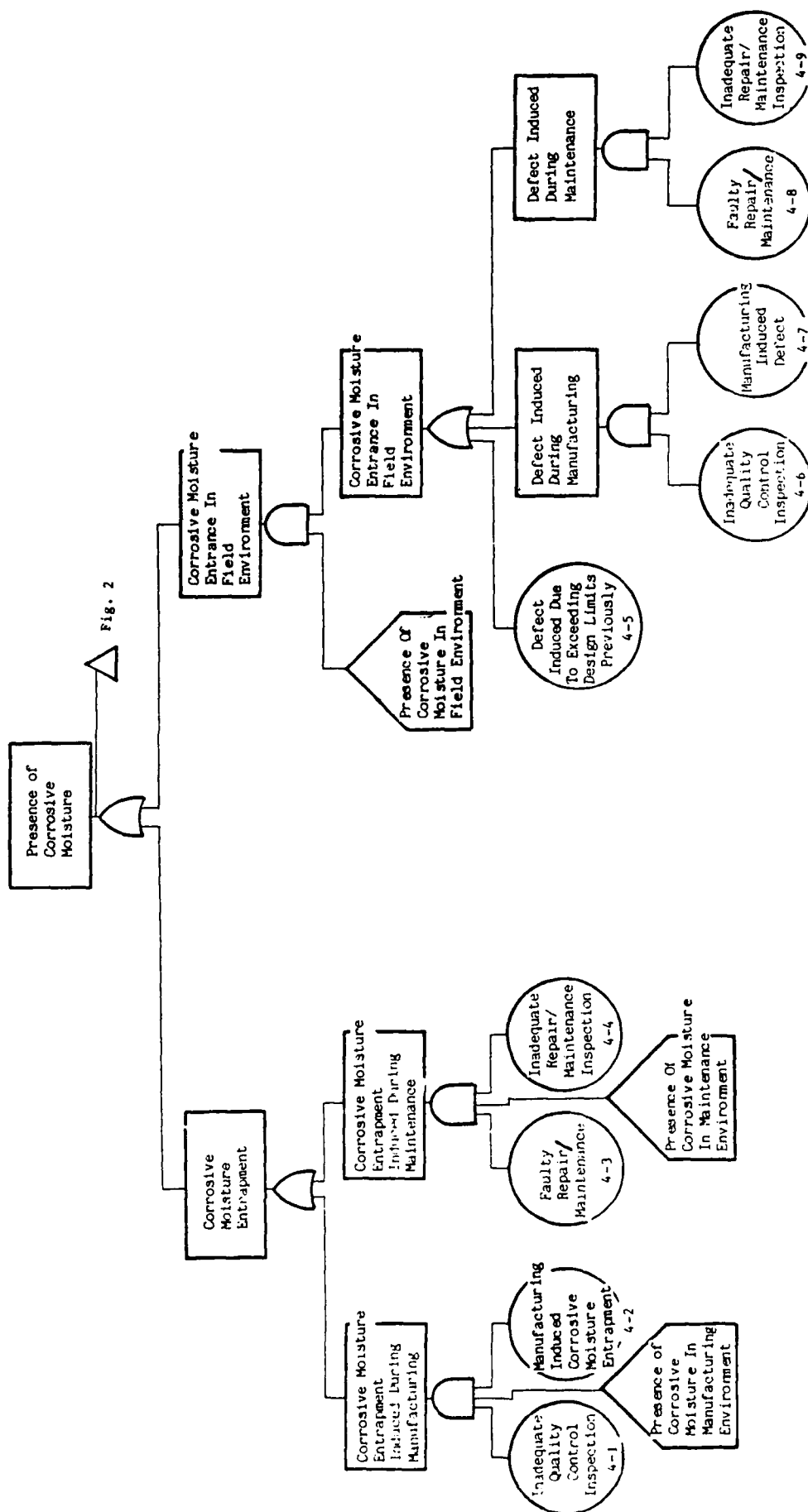
Figure 2  Corrosion-Related Fault Tree (Con't)

Figure 3  Corrosion-Related Fault Tree (Con't)

Figure 4  Corrosion-Related Fault Tree (Con't)

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TABLE 1
FAULT MATRIX

| FAULT TREE ID # | FAULT | FAULT PROB. P(Xi) | COND. PROB. P(I/Xi) | CRIT. |
|---|---|---|---|---|
| 1-1 | Component Not Replaced At Preset Time Limit | 5.0E-02 | 5.7E-08 | 2.9E-09 |
| 1-2 | Impending Failure Not Detected During Preflight Inspection | 9.0E-03 | 3.2E-07 | 2.9E-09 |
| 1-3 | Impending Failure Not Detected During ACE/AACE | 5.0E-02 | 5.7E-08 | 2.9E-09 |
| 1-4 | Impending Failure Not Detected Through Monitoring Of Flight Operation | 9.0E-03 | 3.2E-07 | 2.9E-09 |
| 1-5 | Improper Design | 1.5E-02 | 3.9E-08 | 5.9E-10 |
| 1-6 | Improper Service | 5.0E-02 | 3.9E-08 | 2.0E-09 |
| 1-7 | Improper Installation | 9.0E-03 | 3.9E-08 | 3.5E-10 |
| 2-1 | Failure To Treat Corrosion | 5.0E-02 | 5.0E-09 | 2.5E-10 |
| 2-2 | Imperfect Heat Treatment | 2.5E-02 | 5.2E-09 | 1.3E-10 |
| 2-3 | Lack of Lubricant Coating Between Surfaces | 5.0E-03 | 5.1E-09 | 2.6E-10 |
| 2-4 | Lack of Vibration Control | 5.0E-03 | 5.1E-09 | 2.5E-11 |
| 2-5 | Design Error | 5.0E-03 | 5.1E-09 | 2.5E-11 |
| 2-6 | Plated Surfaces Breakdown | 2.5E-02 | 5.0E-09 | 1.3E-10 |
| 2-7 | Improper Hardware Substitution | 5.0E-03 | 5.0E-09 | 2.5E-10 |
| 3-1 | Moisture Entrapment Induced by Design Flaws | 5.0E-03 | 1.5E-09 | 7.5E-11 |
| 3-2 | Inadequate Quality Control Inspection | 5.0E-11 | 1.3E-10 | 1.3E-11 |
| 3-3 | Manufacturing Induced Moisture Entrapment | 2.5E-02 | 3.7E-10 | 9.3E-11 |
| 3-4 | Faulty Repair/Maintenance | 5.0E-02 | 1.5E-09 | 7.5E-10 |
| 3-5 | Inadequate Repair/Maintenance Inspection | 1.0E-02 | 2.9E-09 | 2.9E-09 |
| 3-6 | Defect Induced Due To Exceeding Design Limits Previously | 5.0E-02 | 1.5E-09 | 7.5E-10 |

TABLE 1
FAULT MATRIX (CON'T)

| FAULT TREE ID # | FAULT | FAULT PROB. P(Xi) | COND. PROB. P(I/Xi) | CRIT. |
|---|---|---|---|---|
| 3-7 | Inadequate Quality Control Inspection | 5.0E-02 | 3.3E-09 | 1.7E-10 |
| 3-8 | Manufacturing Induced Defect | 2.5E-02 | 3.7E-09 | 9.3E-11 |
| 3-9 | Faulty Repair/Maintenance | 5.0E-02 | 1.5E-08 | 7.5E-10 |
| 3-10 | Inadequate Repair/Maintenance Inspection | 1.0E+00 | 2.9E-09 | 2.9E-09 |
| 4-1 | Inadequate Quality Control Inspection | 5.0E-02 | 2.9E-09 | 1.5E-10 |
| 4-2 | Manufacturing Induced Corrosive Moisture Entrapment | 2.5E-02 | 2.9E-09 | 7.3E-11 |
| 4-3 | Faulty Repair/Maintenance | 5.0E-02 | 3.5E-09 | 1.8E-10 |
| 4-4 | Inadequate Repair/Maintenance Inspection | 1.0E+00 | 2.9E-09 | 2.9E-09 |
| 4-5 | Defect Induced Due To Exceeding Design Limits Previously | 5.0E-02 | 3.5E-09 | 1.8E-10 |
| 4-6 | Inadequate Quality Control Inspection | 5.0E-02 | 2.9E-09 | 1.5E-10 |
| 4-7 | Manufacturing Induced Defect | 2.5E-02 | 2.9E-09 | 7.3E-11 |
| 4-8 | Faulty Repair/Maintenance | 5.0E-02 | 3.5E-09 | 1.8E-10 |
| 4-9 | Inadequate Repair/Maintenance Inspection | 1.0E+00 | 2.9E-09 | 2.9E-09 |

TABLE 2
FAULT RANK ORDER

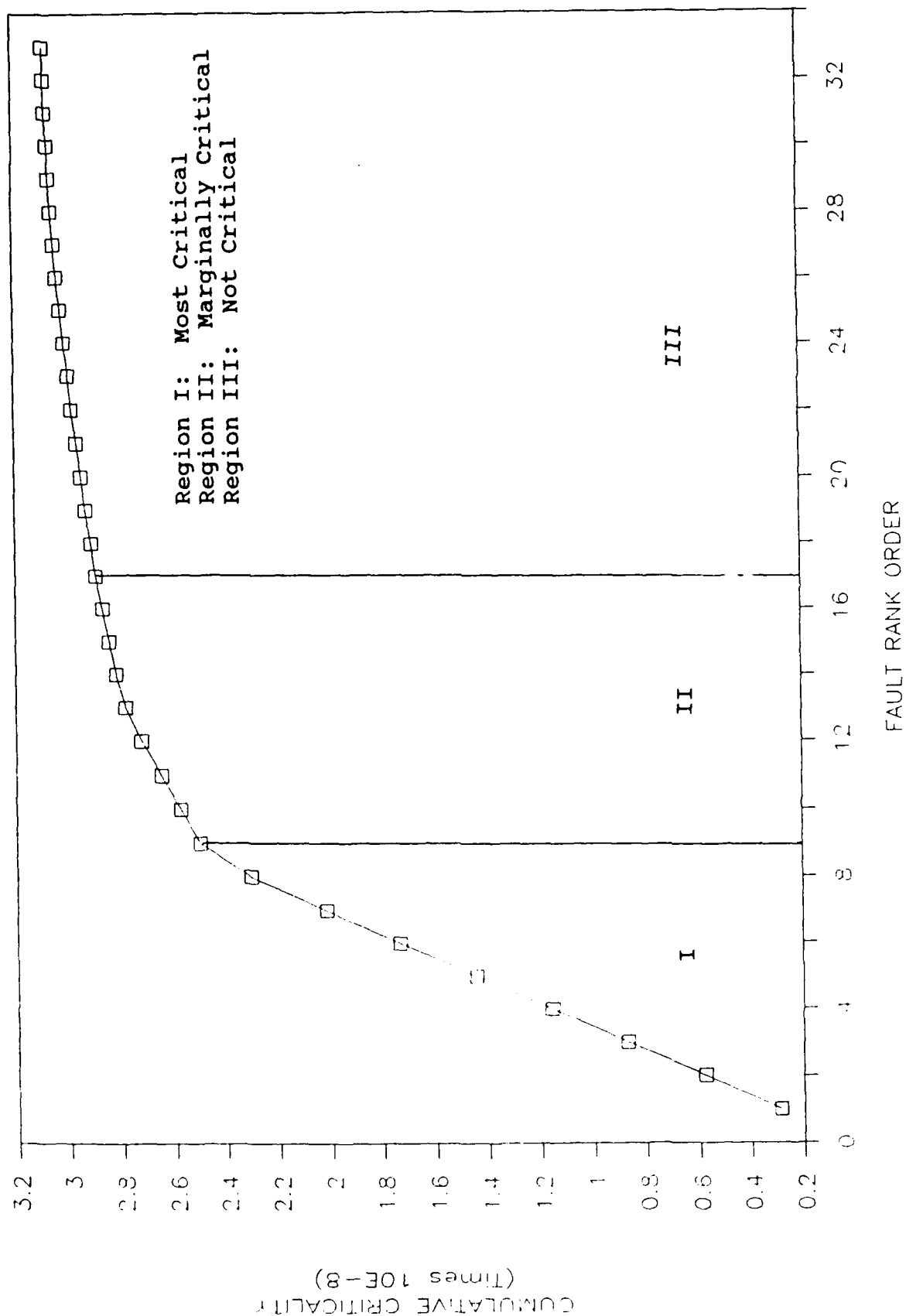| FAULT RANK | FAULT TREE ID # | FAULT | CRITICALITY | CUMULATIVE CRITICALITY |
|---|---|---|---|---|
| **MOST CRITICAL** | | | | |
| 1 | 3-5 | Inadequate Repair/Maintenance Inspection | 2.9E-09 | 2.9E-09 |
| 2 | 3-10 | Inadequate Repair/Maintenance Inspection | 2.9E-09 | 5.8E-09 |
| 3 | 4-4 | Inadequate Repair/Maintenance Inspection | 2.9E-09 | 8.7E-09 |
| 4 | 4-9 | Inadequate Repair/Maintenance Inspection | 2.9E-09 | 1.2E-08 |
| 5 | 1-1 | Component Not Replaced At Preset Time Limit | 2.9E-09 | 1.4E-08 |
| 6 | 1-3 | Impending Failure Not Detected During ACE/AACE | 2.9E-09 | 1.7E-08 |
| 7 | 1-2 | Impending Failure Not Detected During Preflight Inspection | 2.9E-09 | 2.0E-08 |
| 8 | 1-4 | Impending Failure Not Detected Through Monitoring Of Flight Operation | 2.9E-09 | 2.3E-08 |
| 9 | 1-6 | Improper Service | 2.0E-09 | 2.5E-08 |
| **MARGINALLY CRITICAL** | | | | |
| 10 | 3-4 | Faulty Repair/Maintenance | 7.5E-10 | 2.6E-08 |
| 11 | 3-6 | Defect Induced Due To Exceeding Design Limits Previously | 7.5E-10 | 2.7E-08 |
| 12 | 3-9 | Faulty Repair/Maintenance | 7.5E-10 | 2.7E-08 |
| 13 | 1-5 | Improper Design | 5.9E-10 | 2.8E-08 |
| 14 | 1-7 | Improper Installation | 3.5E-10 | 2.8E-08 |
| 15 | 2-2 | Lack of Lubricant Coating Between Surfaces | 2.6E-10 | 2.8E-08 |
| 16 | 2-1 | Failure To Treat Corrosion | 3.5E-10 | 2.9E-08 |
| 17 | 2-7 | Improper Hardware Substitution | 2.5E-10 | 2.9E-08 |
| **NOT CRITICAL** | | | | |
| 18 | 4-2 | Faulty Repair/Maintenance | 1.9E-10 | 2.9E-08 |

TABLE 2
FAULT RANK ORDER (CON'T)

| FAULT RANK | FAULT TREE ID # | FAULT | CRITICALITY | CUMMULATIVE CRITICALITY |
|---|---|---|---|---|
| 19 | 4-5 | Defect Induced Due To Exceeding Design Limits Previously | 1.8E-10 | 2.9E-08 |
| 20 | 4-8 | Faulty Repair/Maintenance | 1.8E-10 | 2.9E-08 |
| 21 | 3-2 | Inadequate Quality Control Inspection | 1.7E-10 | 3.0E-08 |
| 22 | 3-7 | Inadequate Quality Control Inspection | 1.7E-10 | 3.0E-08 |
| 23 | 4-1 | Inadequate Quality Control Inspection | 1.5E-10 | 3.0E-08 |
| 24 | 4-6 | Inadequate Quality Control Inspection | 1.5E-10 | 3.0E-08 |
| 25 | 2-2 | Imperfect Heat Treatment | 1.3E-10 | 3.0E-08 |
| 26 | 2-6 | Plated Surfaces Breakdown | 1.3E-10 | 3.0E-08 |
| 27 | 3-3 | Manufacturing Induced Moisture Entrapment | 9.3E-11 | 3.0E-08 |
| 28 | 3-9 | Manufacturing Induced Defect | 9.3E-11 | 3.1E-08 |
| 29 | 3-1 | Moisture Entrapment Induced by Design Flaws | 7.5E-11 | 3.1E-08 |
| 30 | 4-2 | Manufacturing Induced Corrosive Moisture Entrapment | 7.3E-11 | 3.1E-08 |
| 31 | 4-7 | Manufacturing Induced Defect | 7.2E-11 | 3.1E-08 |
| 32 | 2-4 | Lack of Vibration Control | 2.5E-11 | 3.1E-08 |
| 33 | 2-5 | Design Error | 2.5E-11 | 3.1E-08 |

# FIGURE 5

## CRITICALITY CURVE



Region I: Most Critical
Region II: Marginally Critical
Region III: Not Critical

FAULT RANK ORDER

CUMULATIVE CRITICALITY
(Times 10E-8)

**12.0 SUMMARY REPORT – SwRI PURCHASE ORDER NO. 19359, CHANGE ORDER NO. 1, ITEM C**

## 12.0   SUMMARY REPORT – SwRI PURCHASE ORDER NO. 19359, CHANGE ORDER NO. 1, ITEM C

**RTA**   Reliability Technology Associates
700 Ravinia Place
Orland Park, IL 60462-3750
(312) 349-9590                                  April 18, 1989


Dr. Frank A. Iddings
Director, NTIAC
Southwest Research Institute
Post Office Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Subject:   Summary Report
           SwRI Purchase Order No. 19359, Change Order No. 1, Item C

Dear Frank:

     This letter comprises the subject report.  The information in this letter
has already been submitted to Mr. Lewis Neri of AVSCOM, so this is for your
files.
     The work described herein follows the work previously described to you in
"A Report on the Status of the Development of an NDI Oriented CCAD
Manufacturing Model", submitted October 24, 1988, which will be referred to
here as the "Status Report."  Material in this previous report will be
referenced rather than repeated here.
     In the Status Report, 29 critically short flight safety parts (CSFSPs)
were identified as possible candidates for a flexible manufacturing system
(FMS) cell at Corpus Christi Army Depot (CCAD), for which a model was to be
developed in this investigation.  However, none of these 29 parts turned out
to be a good candidate for the FMS cell at CCAD, so further work on
identifying candidate parts was carried out.
     The CSFSP family finally identified as a candidate for the FMS cell at
CCAD and used as the basis for the model developed here was selected from a
group of 3615 flight safety parts identified by the U.S. Army Aviation Systems
Command (AVSCOM).  These parts were meticulously reviewed, analyzed, evaluated
and screened according to the process shown in Figure 1, which shows the
overall procedure that was used to select the most appropriate part family
and, subsequently, the specific part for analysis, from the 3615 parts.
     There are 174 parts that are both criticality short and flight safety and
require machine operations.  These parts are listed in Table I.  These 174
parts were grouped into appropriate part families following the algorithm
given in Figure 2.  Application of the algorithm to the 174 CSFSPs resulted in
nine part families as follows:

           Part Family No. 1:  Blades and Spurs
           Part Family No. 2:  Large Milling Items
           Part Family No. 3:  Medium Milling Items
           Part Family No. 4:  Small Milling Items
           Part Family No. 5:  Large Turning Items
           Part Family No. 6:  Medium Turning Items
           Part Family No. 7:  Small Turning Items
           Part Family No. 8:  Complex Parts
           Part Family No. 9:  Simple Parts

Tables II through X identify the parts within each of the nine families and their associated on-line machining operations. Tables XI through XIX identify the corresponding off-line manufacturing and inspection operations. From a review of the on/off-line manufacturing and inspection requirements for each part provided in the tables, the part determined most representative for the FMS cell to be modeled for CCAD, from a manufacturing complexity as well as a flight safety standpoint, is the UH-60A spindle (from the eighth part family) and, consequently, this part was selected as the basis to specify the machines and other equipment that would make up the FMS cell.

The overall UH-60A helicopter, with the main rotor spindle assembly highlighted, is shown in the top half of Figure 3; a more detailed illustration of one spindle is given in the bottom half of that figure. The stock material for the spindle is forged titanium. An analysis of the function and capacity of each of the required machining operations was performed to determine the specific requirements for fabricating the spindle. These requirements are as follows:

- Turning ------------ O.D. to 2.6 dia
- Drilling ----------- 0.3 to 1.1 dia
- Boring ------------- I.D. 1.2 to 1.7 dia
- Reaming ------------ Line 1.2 dia
- Threading/Tapping--- Roll 2 5/8 dia to 12
                       threads/inch
- Profiling ---------- 3 - axis
- Milling ------------ Spline 64T
- Grinding ----------- 3 - axis
- Burnishing --------- Roller
- Working (material)-- Shot peening/solid film lube

Figure 4 shows the current spindle manufacturing process. As shown, the current process includes over 30 process steps and three in-process inspections. Figure 5 shows the manufacturing operation sequence for the spindle, if produced using an FMS cell containing the manufacturing operations identified in Tables IX and XVIII and the specifications described above. Producing the spindle in the FMS cell requires about fifty percent fewer machine operations then the current method and only a single manual inspection performed off-line at the completion of the manufacturing operation. The basic quality of the FMS produced spindle is assured through statistically controlled, on-line, real time computer-aided inspection.

After comparing the specific process requirements for the selected CSFSP against the computer numerically controlled (CNC) machine tools available at CCAD (identified in the Status Report), it is apparent that the most practical approach is to purchase new CNC machine tools for each of the required manufacturing operations and to use the existing machines in a backup mode. Specifications for the new machines were then prepared in accordance with the algorithm given in Figure 6. The machine costs were incorporated into the cost-benefit analysis of spindle manufacturing described later in this report.

Figure 7 provides a graphical representation of the FMS cell showing the CNC machines in the proper operational sequence as was depicted in Figure 5. This cell configuration was then evaluated to determine if it is cost-effective to design, install and use the cell to produce parts. If the cell is cost justified, the FMS model, as conceptualized in Figure 5, can be used to plan, program and evaluate the production of parts on a simulated basis.

A cost-benefit analysis was performed to determine the return on investment (ROI) that could be realized if parts were produced by the FMS

cell. This was a comparative analysis that focused on the cost-benefit aspects of manufacturing parts using the FMS cell to existing production methods. The analysis took into account machine investment, direct labor and material costs. The analysis did not take into account any intangible cost factors that may come about from an improvement in quality, faster turn around time, the need for less inventory, and, most importantly, the fact that the use of FMS may be the only practical solution to the CSFSP problem. Also the analysis was made in current dollars. No adjustments were made to account for inflation or present value discounting factors.

The cost-benefit analysis was based on supplying replacement parts from the FMS cell modeled in support of the UH-60A fleet. The UH-60A fleet includes 2251 aircraft. Based on the Army's 10% inventory criteria for a five year period, replacement parts for 225 aircraft are required.

The analysis was based on the cell's being utilized for all Part Family No. 8 parts plus enough Part Family No. 2 parts to bring the cell up to full utilization. The total replacement cost over five years of these parts using existing conventional manufacturing methods and based on a buy for 225 aircraft is $27.6 million. The total replacement cost over five years of producing these parts using the FMS cell, defined by Figure 7, is estimated to be $12.8 million. This estimate is based on the cost of the stock material and the labor associated with setting up and monitoring the CNC machines required for the parts, defined in Table IX and the applicable portion of Table III, and to comply with the specifications described for the parts. It also includes the cost of the off-line manufacturing and final inspection operations. Thus, there is a manufacturing savings of $14.8 million ($27.6 million minus $12.8 million).

A cost of $0.25 million was estimated to maintain the CNC machines as well as the necessary supporting equipment and software over the five year period. Engineering support is estimated to be $3.1 million over five years and technician support is estimated at $2.7 million over five years. The total five year savings is then $8.7 million (manufacturing savings of $14.8 million less maintenance and engineering and technician support).

The purchase cost of the new CNC machines and other manufacturing equipment needed for the FMS cell is estimated to be $4.61 million. A breakdown of this cost is given in Table XX. The costs for utilities, space, fixturing, etc., were estimated at $0.28 million over five years. The total installed facility cost of the FMS cell, then, is $4.89 million ($4.61 million equipment plus $.28 million facilities).

If a savings linear over time is assumed, the total facility cost of $4.89 million will equal the savings in 2 years, 10 months, which is the payback period, well within the Army's short-term return on investment guidelines. Therefore, it is obviously economical to proceed with this FMS cell at CCAD.

There are many further steps that must be taken to establish an actual FMS operating cell at CCAD to produce CSFSPs cost effectively. A key task is to develop the requirements for the production of the parts using the FMS cell planned for CCAD as well as for their procurement from qualified suppliers having FMS capabilities. The production requirements are to cover the essential FMS process parameters, and their characteristics, for the selected CSFSPs, reflecting the capabilities of the CCAD FMS cell. The work includes preparing specifications for incorporation into the applicable depot maintenance work requirement documents or the technical data packages for those parts to be procured by qualified suppliers with FMS capabilities. The work also includes developing the essential FMS process param rs for the

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applicable CSFSPs and their technical characteristics including:
- Throughput
- FSP flexibility (response to change)
- Variability (number of variations within FSP family)
- Quality (AQL - reject rate/rework, MTBF - outgoing from production, product life)
- Batch set-up time
- Turn-around-time
- Downtime
- Efficiency (machine, human)
- True cost (capital investment, operating, inventory)

Also an economic analysis for each FMS part that reflects the manhour, material and net cost savings (as well as schedule and other savings or benefits) resulting from the application of the FMS process must be performed.

This investigation has shown that FMS is a real, practical and cost effective solution to the critically short flight safety part problem at CCAD. There are no significant obstacles in validating the FMS cell, as described in this report, and, once validated, in designing, installing and operating the cell in the production of CSFSPs.

The cell, once operational, can then be used to produce the selected CSFSPs, to serve as a prototype for other government or contractor owned FMS facilities and to support research into new FMS concepts as well as to evaluate improved statistical process control and total quality management techniques.

If you have any questions on this, please contact me at (312) 349-9590.

Sincerely,

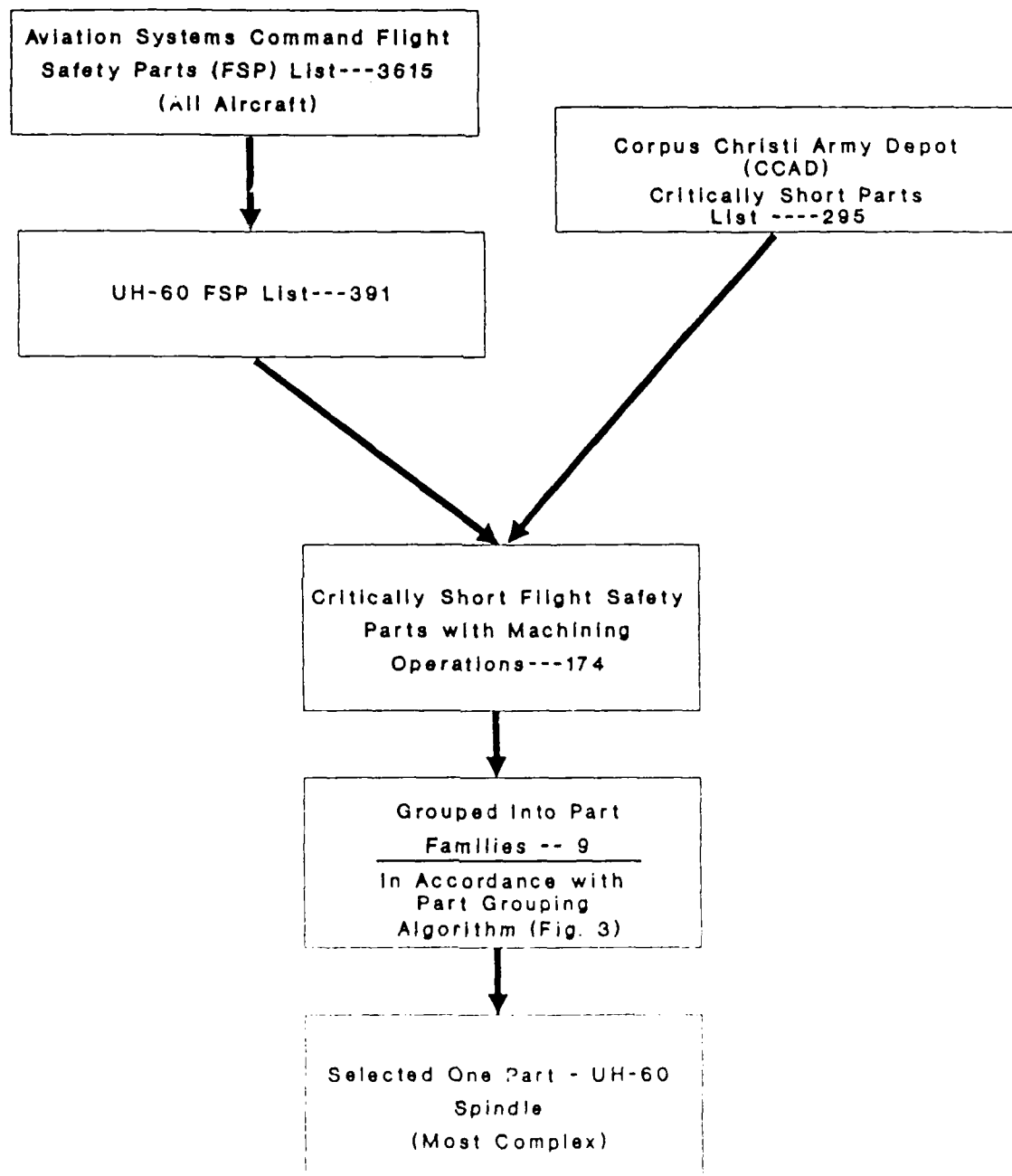*Dan Henry*

C. D. (Dan) Henry III
Program Manager

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Figure 1. Group Technology Screening Process For
Selecting FMS Candidate

Candidate Part

Review
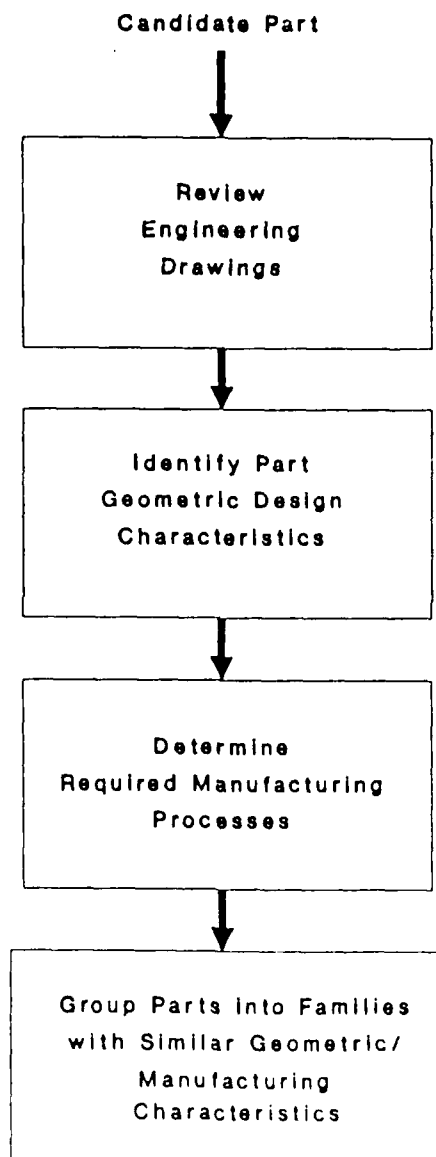Engineering
Drawings

Identify Part
Geometric Design
Characteristics

Determine
Required Manufacturing
Processes

Group Parts into Families
with Similar Geometric/
Manufacturing
Characteristics

Figure 2. Algorithm for Grouping Parts into Families

(a) UH60A Helicopter and Main Rotor Spindle

SPINDLE
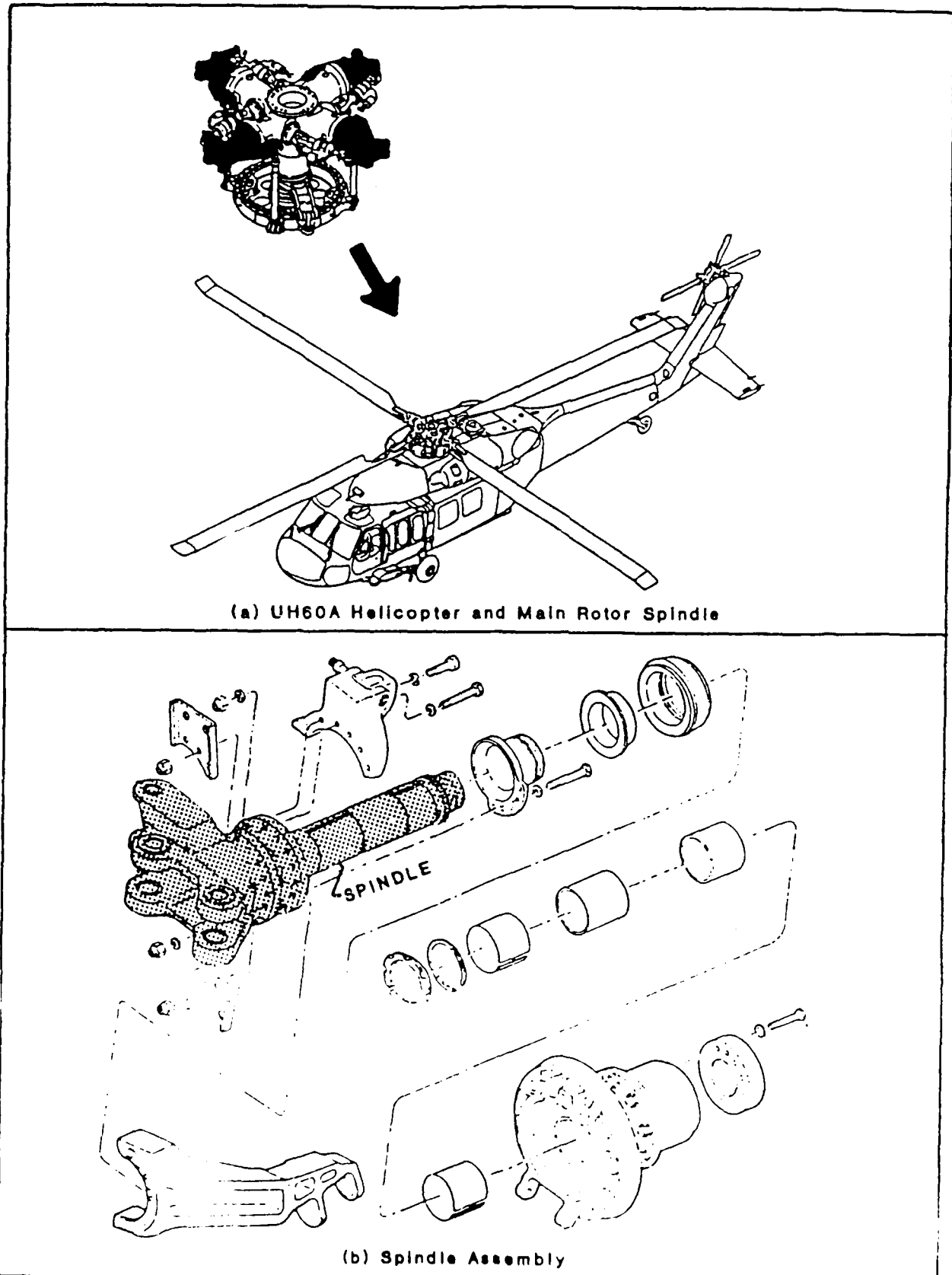
(b) Spindle Assembly

Figure 3  UH60A Helicopter and Spindle Assembly

Figure 4. Current Spindle Manufacturing Process

COMMAND CELL

↓

LOAD JUSTIFIED FIX-
TURE WITH FORGING

AVG

↓

ROUGH MACHINE

AVG

↓

FINISH MACHINE

FORM SPLINE

ROLL THREADS

AVG

↓

WASH

AVG

↓

100% QUALIFY (CMM)

AVG

↓

WIP

COMMAND CELL
FUNCTIONS

AVG

↓

INSERT LINERS
AND BUSHINGS

AVG

↓

100% QUALIFY (CMM)

AVG

↓

WIP

DELIVER TO PRO-
DUCTION CONTROL

↓

STOCK

INSPECTION
POINT

AGV – Automated Guided
Vehicles

WIP – Work In Progress

CMM – Coordinated
Measurement
Machines

↓

SHOT PEEN
FILM LUBE
MARK

↓

100%

↓

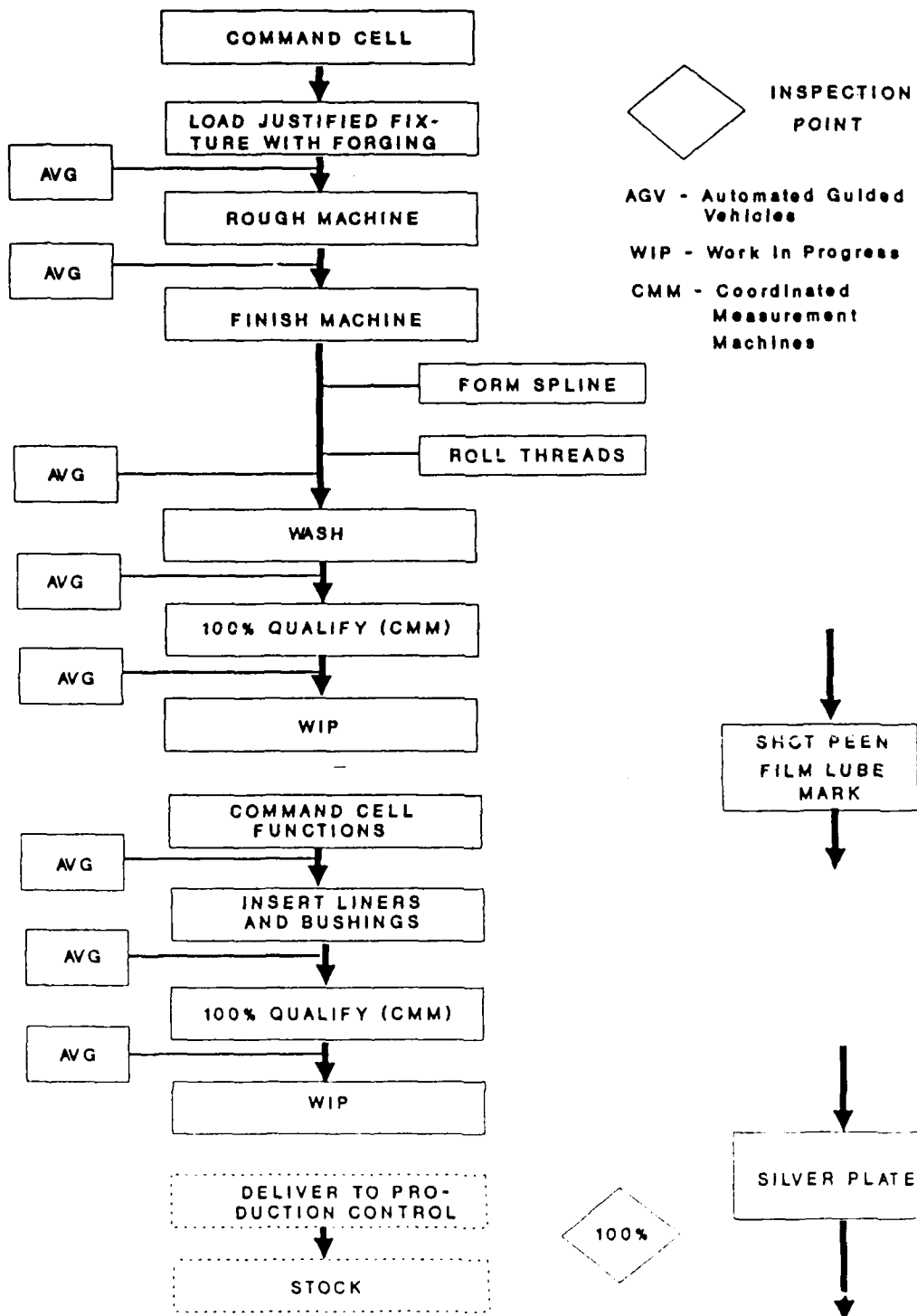SILVER PLATE

↓

Figure 5.  Simulated Spindle FMS Model:
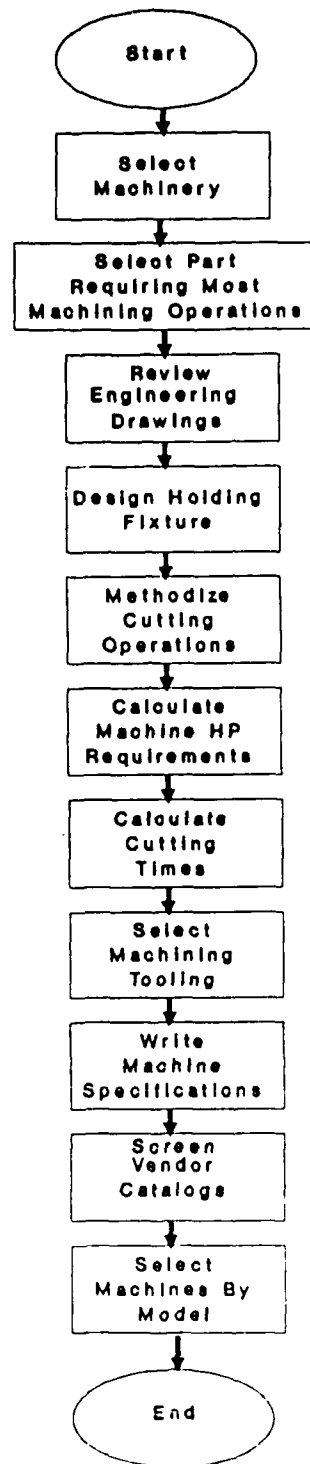MFG Operational Sequence

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Figure 6. Algorithm for the Specification of CNC Machines

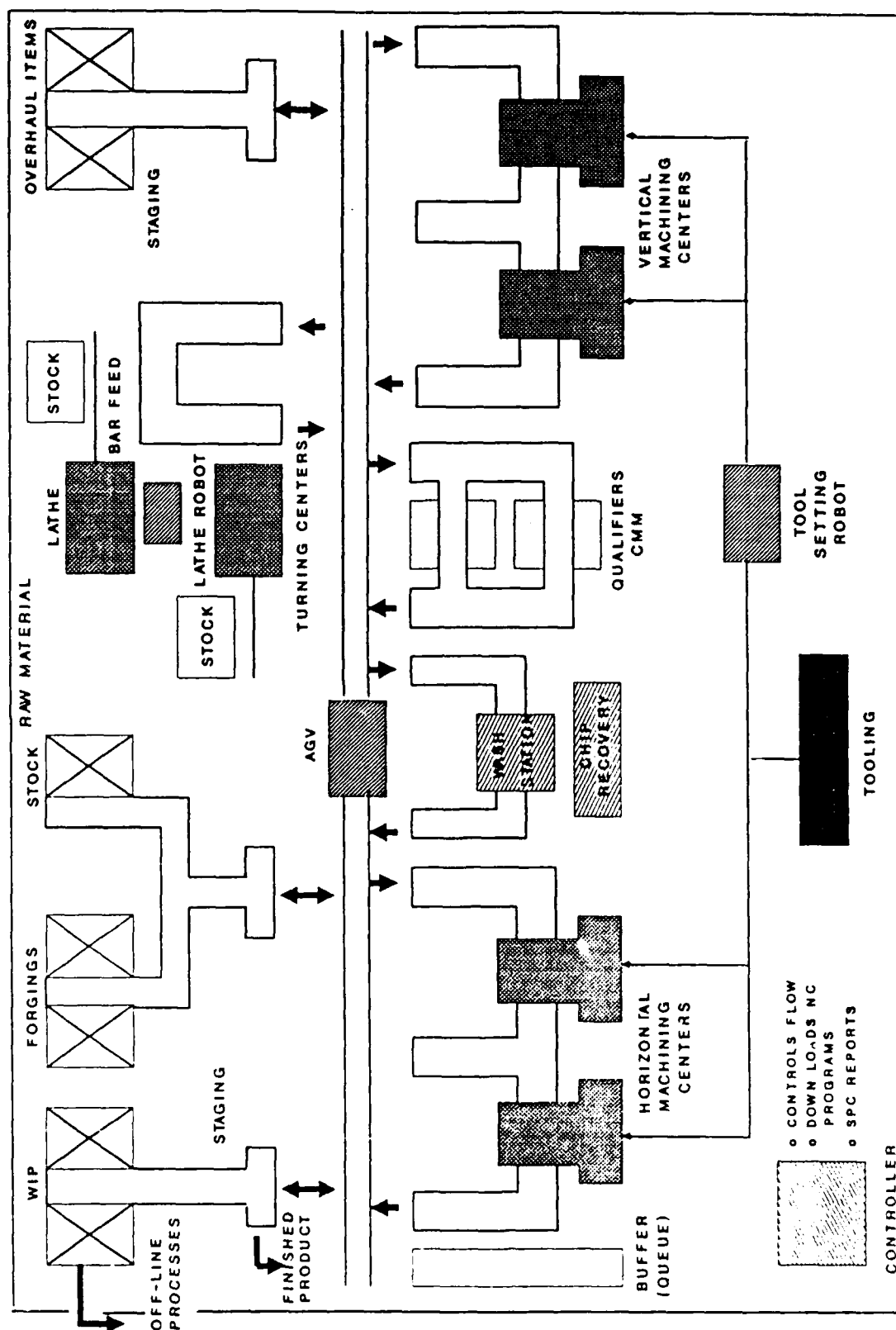Figure 7. FMS Cell Diagram

## TABLE I

### CRITICALLY SHORT FLIGHT SAFETY PARTS
### FOR
### CORPUS CHRISTI ARMY DEPOT
### UH-60A PROGRAM
### NOV 15, 1988

| AIRCRAFT | PART DESCRIPTION | PART NUMBER |
|---|---|---|
| UH-60 | MAIN ROTOR BLADE SPAR | 7015009122102 |
| UH-60 | MAIN ROTOR BLADE SPAR SHEET | 7015009123101 |
| UH-60 | MAIN ROTOR BLADE SPAR PLATE | 7015009124001 |
| UH-60 | SWASHPLATE | 7010408002102 |
| UH-60 | PYLON FITTING ASM | 7020906053041 |
| UH-60 | FITTING | 7021906056041 |
| UH-60 | CANTED HINGED FITTING ASM | 7021905001043 |
| UH-60 | TAIL CONE FITTING ASM | 7021905001045 |
| UH-60 | FITTING | 7021905001105 |
| UH-60 | MAIN TRANSMISSION HOUSING ASM | 7035108110044 |
| UH-60 | HOUSING ASM | 7035108110045 |
| UH-60 | BELLCRANK SUPPORT ASM | 7040008116045 |
| UH-60 | BELLCRANK SUPPORT ASM | 7040008116046 |
| UH-60 | BELLCRANK SUPPORT ASM | 7040008116047 |
| UH-60 | BELLCRANK SUPPORT ASM | 7040008116048 |
| UH-60 | SUPPORT | 7040008116115 |
| UH-60 | HORN | 7010208012105 |
| UH-60 | HORN | 7010208012106 |
| UH-60 | HORN ASM | 7010208111043 |
| UH-60 | SPINDLE HORN ASM | 7010208111044 |
| UH-60 | HORN ASM | 7010208111045 |
| UH-60 | SPINDLE HORN ASM | 7010208111046 |
| UH-60 | SPINDLE HORN ASM | 7010208111047 |
| UH-60 | CUFF ASM | 7015009109041 |
| UH-60 | CUFF | 7015009109101 |
| UH-60 | STABILATOR HINGE FITTING ASM | 7020906052041 |
| UH-60 | HINGE FITTING | 7020906052042 |
| UH-60 | STABILATOR ATTACHMENT FTNG ASM | 7020906052043 |
| UH-60 | ATTACHMENT FITTING ASM | 7020906052044 |
| UH-60 | STABILATOR ATTACHMENT FTNG ASM | 7020906052046 |
| UH-60 | HINGE FITTING | 7020906052101 |
| UH-60 | ATTACHMENT FITTING | 7020906052103 |
| UH-60 | SERVO BEAM FITTING | 7020922103049 |
| UH-60 | SERVO BEAM FITTING ASM | 7020922103050 |
| UH-60 | SERVO BEAM RAIL | 7020922103051 |
| UH-60 | SERVO BEAM RAIL FITTING ASM | 7020922103052 |
| UH-60 | SERVO BEAM FITTING | 7020922103053 |
| UH-60 | SERVO BEAM FITTING ASM | 7020922103054 |
| UH-60 | SERVO BEAM FITTING | 7020922103055 |
| UH-60 | SERVO BEAM FITTING ASM | 7020922103056 |
| UH-60 | FITTING | 7020922103105 |

## TABLE I (CON'T)

| AIRCRAFT | PART DESCRIPTION | PART NUMBER |
|----------|------------------|-------------|
| UH-60 | FITTING | 7020922103106 |
| UH-60 | FITTING | 7020922103107 |
| UH-60 | FITTING | 7020922103108 |
| UH-60 | SERVO BEAM FITTING | 7021902134045 |
| UH-60 | SERVO BEAM FITTING ASM | 7021902134046 |
| UH-60 | SERVO BEAM FITTING | 7021902134047 |
| UH-60 | SERVO BEAM FITTING ASM | 7021902134048 |
| UH-60 | SERVO BEAM FITTING | 7021902134049 |
| UH-60 | SERVO BEAM FITTING ASM | 7021902134050 |
| UH-60 | SERVO BEAM FITTING | 7021902134051 |
| UH-60 | SERVO BEAM FITTING ASM | 7021902134052 |
| UH-60 | FITTING | 7021902134105 |
| UH-60 | FITTING | 7021902134106 |
| UH-60 | FITTING | 7021902134107 |
| UH-60 | FITTING | 7021902134108 |
| UH-60 | SWASHPLATE GUIDE ASM | 7035108227041 |
| UH-60 | PLATE | 7035806612102 |
| UH-60 | BELLCRANK | 7040008101044 |
| UH-60 | BELLCRANK ASM | 7040008101045 |
| UH-60 | BELLCRANK ASM | 7040008101046 |
| UH-60 | BELLCRANK ASM | 7040008101047 |
| UH-60 | BELLCRANK | 7040008101104 |
| UH-60 | SUPPORT | 7040008117046 |
| UH-60 | SUPPORT | 7040008117047 |
| UH-60 | SUPPORT ASM | 7040008117048 |
| UH-60 | BELLCRANK SUPPORT | 7040008117049 |
| UH-60 | BELLCRANK SUPPORT | 7040008117050 |
| UH-60 | SUPPORT | 7040008117103 |
| UH-60 | SUPPORT | 7040008117113 |
| UH-60 | BELLCRANK ASM | 7040008150043 |
| UH-60 | BELLCRANK ASM | 7040008150044 |
| UH-60 | BELLCRANK ASM | 7040008150045 |
| UH-60 | BELLCRANK ASM | 7040008150046 |
| UH-60 | BELLCRANK | 7040008150103 |
| UH-60 | LATERAL LINK | 7040008151045 |
| UH-60 | CLEVIS CONNECTOR | 7040008151046 |
| UH-60 | CLEVIS CONNECTOR | 7040008151047 |
| UH-60 | LINK | 7040008151048 |
| UH-60 | CLEVIS CONNECTOR | 7040008151050 |
| UH-60 | LATERAL LINK | 7040008151060 |
| UH-60 | LATERAL LINK | 7040008151061 |
| UH-60 | LINK | 7040008151106 |
| UH-60 | FITTING ASM | 7020907053043 |
| UH-60 | LOW STABILATOR ACTUATOR FTNG | 7020907053044 |
| UH-60 | FITTING | 7020907053103 |
| UH-60 | FLANGE | 7035108206101 |
| UH-60 | BELLCRANK ASM | 7040008102044 |
| UH-60 | BELLCRANK ASM | 7040008102045 |
| UH-60 | BELLCRANK | 7040008102105 |

TABLE I (CON'T)

| AIRCRAFT | PART DESCRIPTION | PART NUMBER |
|----------|------------------|-------------|
| UH-60 | SUPPORT | 7040008112044 |
| UH-60 | SUPPORT ASM | 7040008112045 |
| UH-60 | SUPPORT | 7040008112107 |
| UH-60 | PUSHROD ASM | 7040001250052 |
| UH-60 | PUSHROD ASM | 7040001250053 |
| UH-60 | PUSHROD ASM | 7040001255103 |
| UH-60 | PUSHROD ASM | 7040001255104 |
| UH-60 | PUSHROD | 7040008155050 |
| UH-60 | PUSHROD ASM | 7040008155054 |
| UH-60 | PUSHROD | 7040008155110 |
| UH-60 | FITTING | 7020906054044 |
| UH-60 | RUDDER FITTING ASM | 7020906055041 |
| UH-60 | TUBE | 7040006700102 |
| UH-60 | WALKING BEAM | 7040008104044 |
| UH-60 | WALKING BEAM | 7040008104045 |
| UH-60 | AFT WALKING BEAM | 7040008104046 |
| UH-60 | AFT WALKING BEAM | 7040008104047 |
| UH-60 | AFT WALKING BEAM | 7040008104048 |
| UH-60 | AFT WALKING BEAM | 7040008104049 |
| UH-60 | BEAM | 7040008104106 |
| UH-60 | BEAM | 7040008104107 |
| UH-60 | SUPPORT | 7040008114047 |
| UH-60 | SUPPORT | 7040008114048 |
| UH-60 | TIE ROD ASM | 7040008114049 |
| UH-60 | TIE ROD ASM | 7040008114050 |
| UH-60 | TIE ROD | 7040008114051 |
| UH-60 | SUPPORT | 7040008114111 |
| UH-60 | ROD | 7040008115043 |
| UH-60 | TIE ROD ASM | 7040008115045 |
| UH-60 | ROD | 7040008115046 |
| UH-60 | LINK | 7040008115049 |
| UH-60 | ROD | 7040008115103 |
| UH-60 | ROD | 7040008155051 |
| UH-60 | ROD | 7040008155052 |
| UH-60 | PUSH ROD ASM | 7040008155053 |
| UH-60 | PUSH ROD ASM | 7040008155055 |
| UH-60 | ROD | 7040008155056 |
| UH-60 | ROD | 7040008155109 |
| UH-60 | ROD | 7040008155111 |
| UH-60 | ROD | 7040008155112 |
| UH-60 | BELLCRANK SUPPORT | 7040008158101 |
| UH-60 | SUPPORT | 7040008158102 |
| UH-60 | PUSHROD | 7040002265114 |
| UH-60 | PUSHROD | 7040002265115 |
| UH-60 | PUSHROD | 7040002265116 |
| UH-60 | PUSHROD | 7040002265117 |
| UH-60 | PUSHROD TUBE | 7040006700101 |
| UH-60 | PUSHROD TUBE | 7040006700103 |
| UH-60 | PUSHROD TUBE | 7040006700106 |

## TABLE I (CON'T)

| AIRCRAFT | PART DESCRIPTION | PART NUMBER |
|----------|------------------|-------------|
| UH-60 | PUSHROD TUBE | 7040008110047 |
| UH-60 | PUSHROD TUBE | 7040008110048 |
| UH-60 | PUSHROD TUBE | 7040008110053 |
| UH-60 | PUSHROD TUBE | 7040008110054 |
| UH-60 | PUSHROD TUBE | 7040008110060 |
| UH-60 | PUSHROD TUBE | 7040008110061 |
| UH-60 | PUSHROD TUBE | 7040008110108 |
| UH-60 | PUSHROD TUBE | 7040008110109 |
| UH-60 | TIE ROD ASM | 7040008111041 |
| UH-60 | TIE ROD ASM | 7040008111042 |
| UH-60 | TIE ROD | 7040008111101 |
| UH-60 | MAIN ROTOR SHAFT | 7035108131102 |
| UH-60 | MAIN ROTOR SHAFT | 7035108131103 |
| UH-60 | MAIN ROTOR SHAFT | 7035108131107 |
| UH-60 | DRAG BEAM | 7025012062101 |
| UH-60 | DRAG BEAM | 7025012062102 |
| UH-60 | DRAG BEAM | 7025012062104 |
| UH-60 | MAIN ROTOR SPINDLE | 7010208101103 |
| UH-60 | MAIN ROTOR HUB | 7010308101101 |
| UH-60 | SHAFT | 7035108186103 |
| UH-60 | GUIDE | 7035108228101 |
| UH-60 | GEAR | 7035806620101 |
| UH-60 | SHAFT | 7035806620102 |
| UH-60 | BOLT | 7020907057101 |
| UH-60 | DRIVE SHAFT ASM | 7036106004043 |
| UH-60 | PUSHROD ASM | 7040002252120 |
| UH-60 | PUSHROD ASM | 7040002252123 |
| UH-60 | PUSHROD ASM | 7040002252124 |
| UH-60 | PUSHROD ASM | 7040002252128 |
| UH-60 | PUSHROD ASM | 7040002252129 |
| UH-60 | PUSHROD ASM | 7040002252130 |
| UH-60 | PUSHROD ASM | 7040002252131 |
| UH-60 | PUSHROD ASM | 7040002252132 |
| UH-60 | PUSHROD ASM | 7040002252133 |
| UH-60 | PUSHROD ASM | 7040002252134 |

Table 11

FMS Part Family No. 1: Blades and Spurs Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
| --- | --- |
| MAIN ROTOR BLADE SPAR | 7015009122102 |
| MAIN ROTOR BLADE SPAR SHEET | 7015009123101 |
| MAIN ROTOR BLADE SPAR PLATE | 7015009124001 |

Table III

FMS Part Family No. 2:  Large Milling Items Machining Operations

## MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| SWASHPLATE | 7010408002102 |
| PYLON FITTING ASM | 7020906053041 |
| FITTING | 7020906056041 |
| CANTED HINGED FITTING ASM | 7021905001043 |
| TAIL CONE FITTING ASM | 7021905001045 |
| FITTING | 7021905001105 |
| MAIN TRANSMISSION HOUSING ASM | 7035108110044 |
| HOUSING ASM | 7035108110045 |
| BELLCRANK SUPPORT ASM | 7040008116045 |
| BELLCRANK SUPPORT ASM | 7040008116046 |
| BELLCRANK SUPPORT ASM | 7040008116047 |
| BELLCRANK SUPPCRT ASM | 7040008116048 |
| SUPPORT | 7040008116115 |

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Table IV

FMS Part Family No. 3:  Medium Milling Items Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| HORN | 7010208012105 |
| HORN | 7010208012106 |
| HORN ASM | 7010208111043 |
| SPINDLE HORN ASM | 7010208111044 |
| HORN ASM | 7010208111045 |
| SPINDLE HORN ASM | 7010208111046 |
| SPINDLE HORN ASM | 7010208111047 |
| CUFF ASM | 7015009109041 |
| CUFF | 7015009109101 |
| STABILATOR HINGE FITTING ASM | 7020906052041 |
| HINGE FITTING | 7020906052042 |
| STABILATOR ATTACHMENT FTNG ASM | 7020906052043 |
| ATTACHMENT FITTING ASM | 7020906052044 |
| STABILATOR ATTACHMENT FTNG ASM | 7020906052046 |
| HINGE FITTING | 7020906052101 |
| ATTACHMENT FITTING | 7020906052103 |
| SERVO BEAM FITTING | 7020922103049 |
| SERVO BEAM FITTING ASM | 7020922103050 |
| SERVO BEAM NAIL | 7020922103051 |
| SERVO BEAM BAIL FITTING ASM | 7020922103052 |
| SERVO BEAM FITTING | 7020922103053 |
| SERVO BEAM FITTING ASM | 7020922103054 |
| SERVO BEAM FITTING | 7020922103055 |
| SERVO BEAM FITTING ASM | 7020922103056 |

Table IV (cont'd)

FMS Part Family No. 3: Medium Milling Items Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| PLATE | 7035800612102 |
| BELLCRANK | 704000810104 |
| BELLCRANK ASM | 704000810105 |
| BELLCRANK ASM | 724000810106 |
| BELLCRANK ASM | 704000810107 |
| BELLCRANK | 704000810104 |
| SUPPORT | 704000811046 |
| SUPPORT | 704000811047 |
| SUPPORT ASM | 704000811048 |
| BELLCRANK SUPPORT | 704000811049 |
| BELLCRANK SUPPORT | 704000311050 |
| SUPPORT | 704000811103 |
| SUPPORT | 704000811113 |
| BELLCRANK ASM | 704000815004 |
| BELLCRANK ASM | 704000315004 |
| BELLCRANK ASM | 724000415004 |
| BELLCRANK ASM | 704000815004 |
| BELLCRANK | 704000815010 |
| LATERAL LINK | 704000815104 |
| CLEVIS CONNECTOR | 704000915104 |
| CLEVIS CONNECTOR | 704000815104 |
| LINK | 704000815104 |
| CLEVIS CONNECTOR | 704000815105 |
| LATERAL LINK | 704000815106 |
| LATERAL LINK | 704000315106 |
| LINK | 704000815106 |

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Table IV    (con't)

FMS Part Family No. 3:  Medium Milling Items Machining Operations

**MACHINING OPERATIONS**

| PART DESCRIPTION | PART NUMBER |
|---|---|
| FITTING | 7020922103105 |
| FITTING | 7020922103106 |
| FITTING | 7020922103107 |
| FITTING | 7020922103108 |
| SERVO BEAM FITTING | 7021902134045 |
| SERVO BEAM FITTING ASM | 7021902134046 |
| SERVO BEAM FITTING | 7021902134047 |
| SERVO BEAM FITTING ASM | 7021902134048 |
| SERVO BEAM FITTING | 7021902134049 |
| SERVO BEAM FITTING ASM | 7021902134050 |
| SERVO BEAM FITTING | 7021902134051 |
| SERVO BEAM FITTING ASM | 7021902134052 |
| FITTING | 7021902134105 |
| FITTING | 7021902134106 |
| FITTING | 7021902134107 |
| FITTING | 7021902134108 |
| SWASHPLATE GUIDE ASM | 70351082270⁄: |

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Table V

FMS Part Family No. 4:  Small Milling Items Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| FITTING ASM | 7020907053043 |
| LOW STABILATOR ACTUATOR FTNG | 7020907053044 |
| FITTING | 7020907053103 |
| FLANGE | 7035108206101 |
| BELLCRANK ASM | 704008102044 |
| BELLCRANK ASM | 704008102045 |
| BELLCRANK | 704008102105 |
| SUPPORT | 704008112044 |
| SUPPORT ASM | 704008112045 |
| SUPPORT | 704008112107 |

Table VI

FMS Part Family No. 5:  Large Turning Items Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| PUSHROD ASM | 7040001250052 |
| PUSHROD ASM | 7040001250053 |
| PUSHROD ASM | 7040001255103 |
| PUSHROD ASM | 7040001255104 |
| PUSHROD | 7040008155050 |
| PUSHROD ASM | 7040008155054 |
| PUSHROD | 7040008155110 |

Table VII

FMS Part Family No. 6: Medium Turning Items Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| FITTING | 702090605404 |
| RUDDER FITTING ASM | 702090605501 |
| TUBE | 704006700102 |
| WALKING BEAM | 704008104044 |
| WALKING BEAM | 704008104045 |
| AFT WALKING BEAM | 704008104046 |
| AFT WALKING BEAM | 704008104047 |
| AFT WALKING BEAM | 704008104048 |
| AFT WALKING BEAM | 704008104049 |
| BEAM | 704008104106 |
| BEAM | 704008104107 |
| SUPPORT | 704008114047 |
| SUPPORT | 704008114048 |
| TIE ROD ASM | 704008114049 |
| TIE ROD ASM | 704008114050 |
| TIE ROD | 704008114051 |
| SUPPORT | 704008114111 |
| ROD | 704008115043 |
| TIE ROD SM | 704008115045 |
| ROD | 704003115046 |

Table VII(cont'd)

FMS Part Family No. 6:  Medium Turning Items Machinig Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LINK | 7040008115049 | | | | X | | | | | | | | X | X | | | | | X | X |
| ROD | 7040008115103 | | X | | X | | | | | | | | X | X | | | | | X | X |
| ROD | 7040008155051 | | | | X | | | | | | | | | | | | | | | |
| ROD | 7040008155052 | | | | X | | | | | | | | | | | | | | | |
| PUSH ROD ASM | 7040008155053 | | | | X | | | | | | | | | | | | | | | |
| PUSH ROD ASM | 7040008155055 | | | | X | | | | | | | | | | | | | | | |
| ROD | 7040008155056 | | | | X | | | | X | X | | | X | X | X | X | | | | |
| ROD | 7040008155109 | | X | | X | | | | X | X | | | X | X | X | X | | | X | X |
| ROD | 7040008155111 | | X | | X | | | | X | X | | | X | X | X | X | | | X | X |
| ROD | 7040008155112 | | X | | X | | | | | | | X | X | X | | | | | X | X |
| BELLCRANK SUPPORT | 7040008158101 | | X | | X | | | | | | | X | X | X | | | | | X | X |
| SUPPORT | 7040008158102 | | X | | X | | | | | | | | | X | | | | | X | X |

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Table VIII

FMS Part Family No. 7: Small Turning Items Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| PUSHROD | 7040002265114 |
| PUSHROD | 7040002265115 |
| PUSHROD | 7040002265116 |
| PUSHROD | 7040002265117 |
| PUSHROD TUBE | 7040006700101 |
| PUSHROD TUBE | 7040006700103 |
| PUSHROD TUBE | 7040006700106 |
| PUSHROD TUBE | 7040008110047 |
| PUSHROD TUBE | 7040008110048 |
| PUSHROD TUBE | 7040008110053 |
| PUSHROD TUBE | 7040008110054 |
| PUSHROD TUBE | 7040008110060 |
| PUSHROD TUBE | 7040008110061 |
| PUSHROD TUBE | 7040008110108 |
| PUSHROD TUBE | 7040008110109 |
| TIE ROD ASM | 7040008111041 |
| TIE ROD ASM | 7040008111042 |
| TIE ROD | 7040008111101 |

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Table IX

FMS Part Family No. 8: Complex Items Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| MAIN ROTOR SHAFT | 7035105131102 |
| MAIN ROTOR SHAFT | 7035108131103 |
| MAIN ROTOR SHAFT | 7035108131107 |
| DRAG BEAM | 7025012062101 |
| DRAG BEAM | 7025012062102 |
| DRAG BEAM | 7025012062104 |
| MAIN ROTOR SPINDLE | 7010208101103 |
| MAIN ROTOR HUB | 7010308101101 |
| SHAFT | 7035108186103 |
| GUIDE | 7035108228101 |
| GEAR | 7035806520101 |
| SHAFT | 7035806620102 |

Table X

FMS Part Family No. 9:   Simple Parts Machining Operations

MACHINING OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| BOLT | 7020907057101 |
| DRIVE SHAFT ASM | 7036106004043 |
| PUSHROD ASM | 7040002252120 |
| PUSHROD ASM | 7040002252123 |
| PUSHROD ASM | 7040002252124 |
| PUSHROD ASM | 7040002252128 |
| PUSHROD ASM | 7040002252129 |
| PUSHROD ASM | 7040002252130 |
| PUSHROD ASM | 7040002252131 |
| PUSHROD ASM | 7040002252132 |
| PUSHROD ASM | 7040002252133 |
| PUSHROD ASM | 7040002252134 |

Table XI

FMS Part Family No. 1:  Blades & Spurs Off Line and Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER |
| --- | --- |
| MAIN ROTOR BLADE SPAR | 7015009122102 |
| MAIN ROTOR BLADE SPAR SHEET | 7015009123101 |
| MAIN ROTOR BLADE SPAR PLATE | 7015009124001 |

Table XII

FMS Part Family No. 2:  Large Milling Items Off Line and Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER |
|---|---|
| SWASHPLATE | 701408002102 |
| PYLON FITTING ASM | 702090605304 1 |
| FITTING | 702090605604 1 |
| CANTED HINGED FITTING ASM | 702190500104 3 |
| TAIL CONE FITTING ASM | 702190500104 5 |
| FITTING | 702190500110 5 |
| MAIN TRANSMISSION HOUSING ASM | 703510811004 4 |
| HOUSING ASM | 703510811004 5 |
| BELLCRANK SUPPORT ASM | 704000811604 5 |
| BELLCRANK SUPPORT ASM | 704000811604 6 |
| BELLCRANK SUPPORT ASM | 7040008116(?) |
| BELLCRANK SUPPORT ASM | 704000811604 8 |
| SUPPORT | 704000811611 5 |

Table XIII.

FMS Part Family No. 3:  Medium Milling Items Off Line and Inspection Operations

OFF LINE AND INSPECTION OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| HORN | 7010208012105 |
| HORN | 7010208012106 |
| HORN ASM | 7010208111043 |
| SPINDLE HORN ASM | 7010208111044 |
| HORN ASM | 7010208111045 |
| SPINDLE HORN ASM | 7010208111046 |
| SPINDLE HORN ASM | 7010208111047 |
| CUFF ASM | 7015009109041 |
| CUFF | 7015009109101 |
| STABILATOR HINGE FITTING ASM | 7020906052041 |
| HINGE FITTING | 7020906052042 |
| STABILATOR ATTACHMENT FTNG ASM | 7020906052043 |
| ATTACHMENT FITTING ASM | 7020906052044 |
| STABILATOR ATTACHMENT FTNG ASM | 7020906052046 |
| HINGE FITTING | 7020906052101 |
| ATTACHMENT FITTING | 7020906052103 |
| SERVO BEAM FITTING | 7020922103049 |
| SERVO BEAM FITTING ASM | 7020922103050 |
| SERVO BEAM RAIL | 7020922103051 |
| SERVO BEAM RAIL FITTING ASM | 7020922103052 |
| SERVO BEAM FITTING | 7020922103053 |

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Table XIII (cont'd)

FMS Part Family No. 3: Medium Milling Items Off Line Inspection Operations

## OFF LINE AND INSPECTION OPERATIONS

| PART DESCRIPTION | PART NUMBER | HEAT TREAT | SHOT PEEN | MAG | PIT GAGE | TEMPER INSP | GAGE | HARDNESS | REID | AA | PI | SI | CHROM | INSP | I | SLIP | IP | PENETRANT | CL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SERVO BEAM FITTING ASM | 7020922103054 | | | | | | | | | | | | | | | X | | X | |
| SERVO BEAM FITTING | 7020922103055 | | | | | | | | | | | | | | | X | | X | |
| SERVO BEAM FITTING ASM | 7020922103056 | | | | | | | | | | | | | | | X | | X | |
| FITTING | 7020922103105 | | | X | | X | | X | | X | | | | | | X | | | |
| FITTING | 7020922103106 | | | X | | X | | X | | X | | | | | | X | | | |
| FITTING | 7020922103107 | | | X | | X | | X | | X | | | | | | X | | | |
| FITTING | 7020922103108 | | | X | | X | | X | | X | | | | | | X | | | |
| SERVO BEAM FITTING | 7021902134045 | | | | | | | | | | | | | | | X | | | |
| SERVO BEAM FITTING ASM | 7021902134046 | | | | | | | | | | | | | | | X | | | |
| SERVO BEAM FITTING | 7021902134047 | | | | | | | | | | | | | | | X | | | |
| SERVO BEAM FITTING ASM | 7021902134048 | | | | | | | | | | | | | | | X | | | |
| SERVO BEAM FITTING | 7021902134049 | | | | | | | | | | | | | | | X | | | |
| SERVO BEAM FITTING ASM | 7021902134050 | | | | | | | | | | | | | | | X | | | |
| SERVO BEAM FITTING | 7021902134051 | | | | | | | | | | | | | | | X | | | |
| SERVO BEAM FITTING ASM | 7021902134052 | | | | | | | | | | | | | | | X | | | |
| FITTING | 7021902134105 | | | X | | X | | X | | X | | | | | | X | | | |
| FITTING | 7021902134106 | | | X | | X | | X | | X | | | | | | X | | | |
| FITTING | 7021902134107 | | | X | | X | | X | | X | | | | | | X | | | |
| FITTING | 7021902134108 | | | X | | X | | X | | X | | | | | | X | | | |
| SWASHPLATE GUIDE ASM | 7035108227041 | | | | | | | | | | | | | | | X | | | |

Table XIII (cont'd)

FMS Part Family No. 3: Medium Milling Items Off Line and Inspection Operations

## OFF LINE AND INSPECTION OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| PLATE | 7035806612102 |
| BELLCRANK | 7040008101044 |
| BELLCRANK ASM | 7040008101045 |
| BELLCRANK ASM | 7040008101046 |
| BELLCRANK ASM | 7040008101047 |
| BELLCRANK | 7040008101104 |
| SUPPORT | 7040008117046 |
| SUPPORT | 7040008117047 |
| SUPPORT ASM | 7040008117048 |
| BELLCRANK SUPPORT | 7040008117049 |
| BELLCRANK SUPPORT | 7040008117050 |
| SUPPORT | 7040008117103 |
| SUPPORT | 7040008117113 |
| BELLCRANK ASM | 7040008150043 |
| BELLCRANK ASM | 7040008150044 |
| BELLCRANK ASM | 7040008150045 |
| BELLCRANK ASM | 7040008150046 |
| BELLCRANK | 7040008150103 |

Table XIII (con't)

FMS Part Family No. 3:  Medium Milling Items Off Line and Inspection Operations

## OFF LINE AND INSPECTION OPERATIONS

| PART DESCRIPTION | PART NUMBER |
|---|---|
| LATERAL LINK | 704008151045 |
| CLEVIS CONNECTOR | 704008151046 |
| CLEVIS CONNECTOR | 704008151047 |
| LINK | 704008151048 |
| CLEVIS CONNECTOR | 704008151050 |
| LATERAL LINK | 704008151060 |
| LATERAL LINK | 704008151061 |
| LINK | 704008151106 |

Table XIV

FMS Part Family No. 4:  Small Milling Items Off Line and Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER | HEAT TREAT | SHOT PEEN | PAINT | TIG WELD | GRIND | HAND GRIND | ANGI GRIND | PRIOR TIME | STRESS RELIEVE | CHEM MILL | INSP PENETRANT | PAINT PRIME | PEEL BELT | CLEAN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FITTING ASM | 7020907053043 | X |  |  |  |  |  |  | X |  |  |  |  |  |  |
| LOW STABILATOR ACTUATOR FTNG | 7020907053044 | X |  |  |  |  |  |  | X |  |  |  |  |  |  |
| FITTING | 7020907053103 |  |  | X |  |  |  | X |  |  |  |  |  |  |  |
| FLANGE | 7035108206101 |  | X | X |  |  |  |  |  |  |  |  |  |  |  |
| BELLCRANK ASM | 7040008102044 |  |  |  |  |  |  |  |  |  |  | X |  |  |  |
| BELLCRANK ASM | 7040008102045 |  |  |  |  |  |  |  |  |  |  | X |  |  |  |
| BELLCRANK | 7040008102105 | X | X |  | X |  |  | X |  |  |  | X |  |  |  |
| SUPPORT | 7040008112044 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| SUPPORT ASM | 7040008112045 | X | X |  |  |  |  |  |  |  |  | X | X |  |  |
| SUPPORT | 7040008112107 |  |  |  |  | X | X |  |  | X | X |  |  |  |  |

Table XV

FMS Part Family No. 5:  Large Turning Items Off Line and Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER | HEAT TREAT | SHOT PEEN | MAG INSPECT | PIT GAGE | THREAD GAGE | GRIND | MAG GRIND | HARD INSP | RADII | AIR GAGE | PROFILE | SURF FIN | CHK | CMM INSP | SURF | INT INSP | PART MARK | PROFILE | LEVEL | CLEAN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PUSHROD ASM | 7040001250052 | X | | | | | X | | | | | | | | | X | | | | | |
| PUSHROD ASM | 7040001250053 | X | | | | | X | | | | | | | | | X | | | | | |
| PUSHROD ASM | 7040001255103 | X | | | | X | X | | | | | X | X | | | X | | | | | |
| PUSHROD ASM | 7040001255104 | X | | | | X | X | | | | | X | X | | | X | | | | | |
| PUSHROD | 7040008155050 | | | | | | | | | X | | | | | | X | | | | | |
| PUSHROD ASM | 7040008155054 | | | | | | | | | | | | | | | X | | | X | X | |
| PUSHROD | 7040008155110 | X | X | X | | | | X | | | | | | | | X | | | X | X | X |

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Table XVI

FMS Part Family No. 6:  Medium Turning Items Off Line and Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER |
|---|---|
| FITTING | 702090654044 |
| RUDDER FITTING ASM | 702090655041 |
| TUBE | 704006700102 |
| WALKING BEAM | 704008104044 |
| WALKING BEAM | 704008104045 |
| AFT WALKING BEAM | 704008104046 |
| AFT WALKING BEAM | 704008104047 |
| AFT WALKING BEAM | 704008104048 |
| AFT WALKING BEAM | 704008104049 |
| BEAM | 704008104106 |
| BEAM | 704008104107 |
| SUPPORT | 704008114047 |
| SUPPORT | 704008114048 |
| TIE ROD ASM | 704008114049 |
| TIE ROD ASM | 704008114050 |
| TIE ROD | 704008114051 |
| SUPPORT | 704008114111 |
| ROD | 704008115043 |
| TIE ROD ASM | 704008115045 |

Table XVI(cont'd)

FMS Part Family No. 6:  Medium Turning Items Off Line Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER |
|---|---|
| ROD | 704008115046 |
| LINK | 704008115049 |
| ROD | 704008115103 |
| ROD | 704008155051 |
| ROD | 704008155052 |
| PUSH ROD ASM | 704008155053 |
| PUSH ROD ASM | 704008155055 |
| ROD | 704008155056 |
| ROD | 704008155109 |
| ROD | 704008155111 |
| ROD | 704008155112 |
| BELLCRANK SUPPORT | 704008158101 |
| SUPPORT | 704008158102 |

Table XVII

FMS Part Family No. 7:  Small Turning Items Off Line and Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER |
|---|---|
| PUSHROD | 7040002265114 |
| PUSHROD | 7040002265115 |
| PUSHROD | 7040002265116 |
| PUSHROD | 7040002265117 |
| PUSHROD TUBE | 7040006700101 |
| PUSHROD TUBE | 7040006700103 |
| PUSHROD TUBE | 7040006700106 |
| PUSHROD TUBE | 7040008110047 |
| PUSHROD TUBE | 7040008110048 |
| PUSHROD TUBE | 7040008110053 |
| PUSHROD TUBE | 7040008110054 |
| PUSHROD TUBE | 7040008110060 |
| PUSHROD TUBE | 7040008110061 |
| PUSHROD TUBE | 7040008110108 |
| PUSHROD TUBE | 7040008110109 |
| TIE ROD ASM | 7040008111041 |
| TIE ROD ASM | 7040008111042 |
| TIE ROD | 7040008111101 |

Table XVIII

FMS Part Family No. 8:  Complex Items Off Line and Inspection Operations

OFF LINE AND INSPECTION OPERATIONS

| PART DESCRIPTION | PART NUMBER | HEAT TREAT | SHOT PEEN | MAG PARTICLE INSPECT | PENETRANT INSPECT | GRIND | GRIND | MACHINE | HARD INSPECT GRIND | MARK ANODIZE | PAINT IDENTIFICATION | SPECIAL PROCESS | TITLE REPAIR | SURFACE INSPECT | CLEAN LAP | SIZE VISUAL | PROFILE INSPECT | DIMENSIONAL INSPECT | COMPLETE FINAL INSPECT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAIN ROTOR SHAFT | 7035108131102 | X | X |  |  | X | X |  |  |  |  |  |  |  |  |  | X | X |  |
| MAIN ROTOR SHAFT | 7035108131103 | X | X | X |  | X | X |  |  | X |  | X |  |  |  |  | X | X |  |
| MAIN ROTOR SHAFT | 7035108131107 | X | X | X |  | X |  |  |  | X |  | X |  |  |  |  | X | X |  |
| DRAG BEAM | 7025012062101 | X |  |  |  | X |  |  | X | X |  | X |  |  | X | X | X |  |  |
| DRAG BEAM | 7025012062102 | X | X |  | X | X |  |  | X | X |  | X |  |  | X | X | X |  |  |
| DRAG BEAM | 7025012062104 | X |  |  |  | X |  |  | X |  |  | X |  |  | X | X | X |  |  |
| MAIN ROTOR SPINDLE | 7010308101103 |  |  | X |  |  | X |  |  |  |  | X |  |  |  |  | X |  |  |
| MAIN ROTOR HUB | 7010308101101 |  |  | X |  |  | X |  |  |  |  | X |  |  |  |  | X |  |  |
| SHAFT | 7035108186103 | X |  |  |  |  |  |  | X |  |  |  |  | X |  | X | X |  |  |
| GUIDE | 7035108228101 | X | X |  |  |  |  |  | X |  |  |  | X |  |  |  | X |  |  |
| GEAR | 7035806620101 |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  | X | X | X |
| SHAFT | 7035806620102 | X | X | X |  |  |  |  |  |  |  |  |  | X |  |  |  |  |  |

Table XIX

FMS Part Family No. 9:  Simple Parts Off Line and Inspection Operations

**OFF LINE AND INSPECTION OPERATIONS**

| PART DESCRIPTION | PART NUMBER | HEAT TREAT STRAIGHTEN | SHOT PEEN | PIT GAGE INSPECT | TEST GAGE | GRIND DIA GRIND | GRIND DIA GRIND | MAGNAFLUX INSPECT | HARDNESS INSPECT | RADIUS INSPECT | ANODIZE | PLATE | SURF FINISH INSPECT | CHEM INSPECT | CHROMATE | SURF VISUAL INSP | PIPE PASSIVATE | PIPE INSPECT | EMPLY INSP | CLEAN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BOLT | 7020907057101 | X | X | X | X |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |
| DRIVE SHAFT ASM | 7036106004043 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| PUSHROD ASM | 7040002252120 |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| PUSHROD ASM | 7040002252123 |  |  | X |  |  |  | X | X |  |  |  | X | X |  |  | X | X |  |  |
| PUSHROD ASM | 7040002252124 |  |  | X |  |  |  | X | X |  |  |  | X | X |  |  | X | X |  |  |
| PUSHROD ASM | 7040002252128 |  |  | X |  |  |  | X | X |  |  |  | X | X |  |  | X | X |  |  |
| PUSHROD ASM | 7040002252129 |  |  | X |  |  |  | X | X |  |  |  | X | X |  |  |  |  |  |  |
| PUSHROD ASM | 7040002252130 |  |  |  |  |  |  | X | X |  |  |  | X | X |  |  |  |  |  |  |
| PUSHROD ASM | 7040002252131 |  |  | X |  |  |  | X | X |  |  |  | X | X |  |  |  |  |  |  |
| PUSHROD ASM | 7040002252132 |  |  | X |  |  |  | X | X |  |  |  |  | X |  |  | X | X |  |  |
| PUSHROD ASM | 7040002252133 |  |  | X |  |  |  | X | X |  |  |  | X | X |  |  |  |  |  |  |
| PUSHROD ASM | 7040002252134 |  |  | X |  |  |  | X | X |  |  |  | X | X |  |  | X | X |  |  |

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TABLE XX
CNC MACHINE/EQUIPMENT COST

| CNC MACHINE/EQUIPMENT | COST ($1,000.) |
|---|---|
| Turning Centers | 750 |
| Horizontal Machining Centers | 450 |
| Automated Guided Vehicles | 40 |
| Wash Station | 100 |
| Central Coolant and Chip Recovery Station | 150 |
| Coordinated Measurement Machines | 800 |
| Vertical Machine Centers | 600 |
| Controller (Includes Operating System and Application Software) | 120 |
| Tooling Storage | 100 |
| Tool Setting Robot | 1500 |
| TOTAL | $4.61 Million |

# 13.0 MACHINE SUPPORT ELEMENT ISSUES IN FMS CELL DEFINITION

# 13.0  MACHINE SUPPORT ELEMENT ISSUES IN FMS CELL DEFINITION

MACHINE SUPPORT ELEMENT ISSUES
IN FMS CELL DEFINITION

Prepared for:

Depot Engineering & RCM
Support Office
U.S. Army Aviation Systems Command
Corpus Christi, Texas 78419-6195

Prepared by:
Reliability Technology Associates
700 Ravinia Place
Orland Park, Illinois 60462-3750

FOREWORD

The work described herein was performed for the U.S. Army Aviation
Systems Command (AVSCOM), Depot Engineering and RCM Support Office (DERSO), as
part of AVSCOM's program to assess the extent of corrosion in Army aircraft
and its cost, investigate non-destructive inspection (NDI) techniques for
corrosion, and formulate specific recommendations for detecting corrosion in
new and fielded Army aircraft. The purpose of the specific effort for which
this report gives the results was to review the NDI data and information from
the overall program in order to support AVSCOM DERSO in defining a flexible
manufacturing system (FMS) cell at Corpus Christi Army Depot (CCAD) for
support of corrosion control by addressing three machine support element
issues: control software, training, and parts flow simulation. It was
conducted as part of a Special Task under the auspices of the Nondestructive
Testing Information Analysis Center (NTIAC) at Southwest Research Institute
(SwRI) under Contract No. DLA900-84-C-0910, CLIN 0001BM. This study was
performed under subcontract by Reliability Technology Associates (RTA). At
RTA, Dr. C. D. Henry was program manager and principal investigator. Dr. F.
A. Iddings was SwRI's technical monitor for the study. At AVSCOM, this study
was monitored by Mr. R.G. DuCote, who provided necessary data and other
information used as input.

## TABLE OF CONTENTS

## 1.0 INTRODUCTION

This report given the results of a special effort to review non-destructive inspection (NDI) data and information resulting from the Army aircraft NDI oriented corrosion control program in order to support the U.S. Army Aviation Systems Command (AVSCOM) Depot Engineering and RCM Support Office (DERSO) in defining a flexible manufacturing system (FMS) cell for support of corrosion control at Corpus Christi Army Depot (CCAD).

In particular the effort addresses the NDI methods investigated under the corrosion control program and selected machine support element issues, including control software, training, and parts flow simulation. Elements of issues which were addressed included:

- Control Software
  - What alternative are available in controlling machines with controllers of different manufacture which are not intended for integration? What is their impact on the flexible manufacturing cell and the incorporation of candidate NDI corrosion prevention methods?
  - What elements of control should be distributed and what elements, centralized?
  - What should be the control software approach to ensure smooth expansion and the incorporation of further NDI corrosion prevention methods in the future?
- Training
  - What skill levels are required to maintain the automated concept and to successfully incorporate the NDI corrosion prevention concepts?
  - How can the number of personnel best be minimized?
- Parts Flow Simulation
  - Should the simulation software be fully contracted, purchased, or partially contracted and partially purchased?

An evaluation of the information and a description of the elements addressed are given in the following three sections of this report for inclusion in the FMS cell definition document.

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## 2.0 CONTROL SOFTWARE

FMS cell control must tie everything in the cell together by generating detailed task requirements and passing these on to each basic component of the cell. Each component, then, must perform, according to the instructions passed along to it, like any standard machine tool – that is, dependably, accurately, and quickly. The long range goal of cell control should be the complete integration of all the cell elements with the emphasis on speed, accuracy, and reliability. All information and control locations should in theory be able to communicate with all others. This is less a technical problem than a management problem. Information must belong to any sector of the cell that needs it. Each sector must be able to access the relevant information wherever it is available.

Unfortunately the standards of FMS cell control technology have not yet completely gotten together. Some cell control has been based on software; other has been based on sensor reading. Cell control is very application-specific. Control software might be made into a generic product, but it will have to be able to integrate with application-oriented packages.

Cell control vendors have traditionally emanated from two very different industry mindsets: computer systems manufacturers and the control systems manufacturers. Control vendors, coming from backgrounds in switching gears and servomechanisms, have tended to be more work specific. Computer vendors, having come out of the tradition of "the universal thinking machine", have tended to see all process as data processing, or more recently as information processing. One side has dealt with differences and has made a business out of it; the other wants to get rid of difference as soon as possible and get down to business. Recent alliances which are designed to facilitate the integration of FMS cell control, like that between Digital Equipment Corporation (DEC) and the Allen-Bradley Company, have helped bring together these two starting points in dealing with FMS cell control issues. There is also a growing pool of people who have a sound understanding of both computer and FMS cell control operation and machining, and this will help smooth the way to successful FMS cell control implementation.

The FMS cell control approach which seems to be most applicable to the CCAD situation is a cell controller with a personal computer that drives a variety of such operator/attendant support functions as monitoring tool wear

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and oil pressure, diagnostics, tool change, and statistical process control software modules. Cell control manufacturers and software houses are teaming up to meet requirements for this approach. Many elements of cell control are common to all applications, and this helps hold down costs.

Particular FMS cell control products which are applicable to the CCAD situation include the CIM-Star DX system from GE Fanuc Automation North America Inc. (Route 29 and 606, Charlottesville, VA 22901, (804) 978-5000) which is built around Digital Equipment Corporation's MicroVAX computer with integrated hardware and software which can be tailored to CCAD requirements. The alliance between the Allen-Bradley Company Inc. (1201 South Second Street, Milwaukee, WI 53204, (414) 382-2000) and DEC has resulted in a jointly developed FMS cell control system, the Pyramid Integrator, which is built on such hardware, software, and communications products as the Allen-Bradley PLC-5/250 programmable controller, the configurable CVIM vision module, and DEC's MicroVAX information processor modules. CIMCORP/Factory Controls (P.O. Box 2032, Aurora, IL 60507-2032, (312) 851-2220) offers the CIMCELL cell controller which is adaptable to the CCAD situation. Automation Intelligence, Incorporated, (1200 West Colonial Drive, Orlando, FL 32804-7194, (305) 843-7030), which is an IBM Business Partner, tailors their cell software to multivendor and step-by-step automation requirements like those faced by CCAD. Giddings & Lewis Electronics Company (P.O. Box 1658, Fond du Lac, WI 54936-1658, (414)921-7100) offers a library of 80 software programs that can be easily customized to serve customers like CCAD. Two very small companies that specialize in software systems as the "middlemen" between controller-computer systems and machining units are FASTech Integration Inc. of Waltham, Massachusetts, and CAD/CAM Integration (80 Winn Street, Woburn, MA 01801, (617) 933-9500).

Several companies, including those cited in the previous paragraphs, were contacted regarding control and software support elements required for the FMS cell at CCAD, and some have provided specific information. The MSI Corporation (28W152 Commercial Avenue, Barrington, IL 60010, (312) 382-2330) recommends using the Advanced Logic Information Exchange (ALIX) industrial computer control based on the "AT" type architecture as the centralized CPU and stand alone intelligent input-output modules distributed to each machine in the cell. Each machine would contain an alphanumeric display terminal with video screen for user friendly operation. The ALIX Industrial Control would

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perform machine part program loading, statistical process control, on-line diagnostics, run-time self-check of each machine in the cell, and other functions that CCAD may require. ALIX control software can be provided in Assembly, Basic, "C", Fourth, or Pascal language. This would be the choice of CCAD.

The Wiedemann Division of Warner & Swasey, a Cross & Trecker Company, (211 South Gulph Road, King of Pressia, PA 19406, (215) 265-2000) also reviewed the FMS cell and recommended writing custom integration software to handle the situation. Wiedemann has an extensive and comprehensive software library and develops their own software, so they could prepare the special software package required for CCAD's needs. Their FMS cell controls are state-of-the-art using Allen Bradley Five family controllers linked directly to a Digital MicroVAX computer.

The next step in addressing software for the FMS cell is to look in more detail at each of the alternatives and approaches highlighted above, and others that are identified in the interim, in light of the FMS cell eventually defined, and to choose the one which is most applicable to the situation. This will entail ultimately working with application engineers at a vendor to tailor something for CCAD.

## 3.0 TRAINING

Attention to worker training will be essential to the well-planned introduction of an FMS cell at CCAD. Skilled and FMS trained mechanics, electricians, operators, and software engineers will be required to operate and maintain the cell. To maintain the automated concept generally higher levels of skill are demanded, so worker training must become continuous, integrated, and comprehensive. Workers in the FMS cell must understand the interdependence of machines, the cell, processes, and facilities and must realize the far-reaching consequences of malfunction. They must be trained generally for the new procedures, flexibility, integration, and teamwork required in the cell; they must learn to operate or work with the specific equipment in the cell; and they must become familiar with the total social-industrial change resulting from the introduction of flexible manufacturing. They must have the skills, competencies, and authority to be able to detect and correct their own errors.

An important question in the introduction of the FMS cell will be whether to upgrade or downgrade worker positions, that is, whether to give workers more responsibility in regard to the FMS cell (upgrade their positions) or to give workers lower level assignments (downgrade their positions) and in turn downgrade line management. In downgrading, lower-level management and support personnel would attend to major problems and decisions in the cell, while workers would be assigned only the simpler, less analytical tasks. With downgrading it is easier to train and monitor the workforce and easier to replace workers. But some managers and perhaps some technician-level personnel would be performing lower-level jobs for higher-level pay. Furthermore, with downgrading, the workforce would be less likely to learn to recognize problems in the cell and to be attuned and alert to problems in the cell.

Upgrading would increase the training demand, but at the same time help create a strong loop between those who monitor and recognize problems. Upgrading also would make better use of management.

Another issue that CCAD management must evaluate will be whether to organize the workforce in the FMS cell into work teams. Work teams would encourage joint work efforts, facilitate sharing of information, and generate a feeling a responsibility in the workforce. Teams commonly have a range of

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responsibilities, allowing or even requiring team members to float from one job or skill to another. Some determination must be made about the responsibilities of the teams, how they should be organized, how they should be trained, and how to get the most out of the teams. Training to achieve a certain team competence will be helpful during startup, but the goal should be to ultimately get all the team members as much training as possible, independent of the team.

Workers should be involved right from the start of planning for the FMS cell and should be able to participate in its design as well as support the cell.

Effective training for the FMS cell must be continuous and come in a variety of ways from a variety of sources. This not only will increase the competence of individual CCAD employees with the FMS cell as being defined, but will also enable CCAD to respond to technological advances. Such programs make instruction available when employees need it, not just when it is convenient.

Another decisive element in worker training is when it is done. CCAD employees must have achieved the skill level required before operation can begin effectively.

Where to go for training is another question. Customized programs can be contracted to zero in on what CCAD is trying to accomplish. Off-site educators are principally vocational schools and community colleges, although consultants, vendors, and professional organizations also provide various forms of off-site training. Choosing or developing an effective training program involves performing a training evaluation that identifies needs and determines goals, establishing resources, conducting research, instituting the plan and evaluating its effectiveness. The most important points to look for in a training program are given in Table 1. The different types of training methods available and their relative merits are given in Table 2. Possible sources for training programs are given in Table 3.

Table 1   Points To Look For in a Training Program

- Proper content

- Compatibility with upper-management training

- No disruption to CCAD production schedules

- Speed in training

- A program that employees will relate to and learn from

- A program that can be presented by employees without dependence
  on outside trainer or consultants

- A program that will not tie up the CCAD's experts in that field
  of instruction, but instead will free them to work on
  implementation issues

- Ability to accommodate refresher and new-hire training after
  initial training is complete

- Cost

- Suitability to management style and the delegation of authority

- Measurable results

- Proven results

- Development by people with the right credentials

- Reputable supplier

- The opportunity to evaluate the program before purchase.

- A practical, not a theoretical, orientation

- Customer endorsements

**Table 2   The Relative Merits of Training Methods**

| | Traditional Classroom Lecture | Hands-on Training | Video-assisted Instruction | Computer-based Training | Interactive-video Instruction |
|---|---|---|---|---|---|
| Presentation-to-student ratio | One-to-many | One-to-one; One-to-many | One-to-one; One-to-many | One-to-one | One-to-one |
| Self-paced | No | Somewhat | When one-to-one, yes | Yes | Yes |
| Modular | Yes | Yes | Yes | Yes | Yes |
| Interactive | Sometimes | Yes | No | Yes | Yes |
| Self-testing | No | Yes | No | Yes | Yes |
| Updateable | Yes | Yes | Yes, but expensive | Yes, but expensive | Yes, but very expensive |
| Uniformity of instruction | Fair | Fair | Excellent | Excellent | Excellent |
| Development time per unit of instruction* | 100 hours per hour | 1 man-month per day | 100 hours per hour | 100 hours per hour | 4 months per video disc |
| Development cost per unit of instruction* | $5000-$10,000 per hour | $8000-$15,000 per day | $10,000-$20,000 per hour | $2000-$20,000 per hour | $100,000 or more per video disc |
| Price of package (typical)* | $100 on up; $500-$1200 per week; management seminars, $1200 on up | $500 on up | $5000-$8500; $20,000-$30,000; plus hardware | $2000-$20,000 plus hardware ($5000 typical) | Generic: $1000 plus hardware ($10,000 typical) |
| Leasing available | No | No | Yes | Yes | Yes |
| Requirements: | | | | | |
| Classroom | Yes | Yes | Depends on number of attendees | No | No |
| High student attendance for presentation to be cost-justified | Yes | Usually | No | No | No |
| Instructor | Yes | Yes | Optional | Optional | Optional |
| Printed Material | Typically required | Typically required | Optional | Optional | Optional |
| Computer | No | As required | No | Yes | Yes |
| Video tapes or video discs | No | As required | Yes | No | Yes |

*Highly dependent on such factors as subject matter, availability matter sources, training complexity, and quality of training.

Table 3  Sources for Training Programs

| | |
|---|---|
| Advanced Systems, Inc.<br>155 East Algonquin Road<br>Arlington Heights, IL 60005<br>(312)981-1500  (800)822-2398 | Lawrence A. Heller Associates<br>225 West Swissvale Avenue<br>Pittsburgh, PA 15218<br>(412)244-0670 |
| Allen-Bradley Company Inc.<br>1201 South Second Street<br>Milwaukee, WI  53204<br>(414)382-2000 | Manufacturers Technologies Inc.<br>59 Interstate Drive<br>West Springfield, MA 01089<br>(413)733-1972 |
| Am/Tech/Developments<br>4533 Lakeview Drive<br>Beaverton, MI 48612<br>(517)435-3229 | National Technological University<br>P.O. Box 700<br>Fort Collins, CO 80522<br>(313)491-6092 |
| Arthur Andersen and Compnay<br>1801 Maple Street<br>Evanston, IL 60201<br>(312)491-5988 | Oliver Wight Companies<br>P.O. Box 435<br>Newbury, NH 03255<br>(603)763-5926   (800)258-3862 |
| Brown & Sharpe Manufacturing Company<br>P.O. Box 456<br>North Kingstown, RI 02852<br>(401)886-2000 | Philip Crosby Associates, Inc.<br>806 West Morse Boulevard<br>P.O. Box 2369<br>Winter Park, FL 32750<br>(305)645-1733 |
| Cincinnati Milacron Inc.<br>4701 Marburg Avenue<br>Cincinnati, OH 45209-1025<br>(513)841-8100 | Rath & Strong, Inc.<br>21 Worthen Road<br>Lexington, MA 02173<br>(617)861-1700 |
| Community College of Allegheny County<br>800 Allegheny Avenue<br>Pittsburgh, PA 15233<br>(412)323-2323 | Reliability Technology Associates<br>Engineering Applications Group<br>700 Ravinia Place<br>Orland Park, IL 60462-3750<br>(312)349-9590 |
| Concourse Corporation<br>11441 Valley View Road<br>Minneapolis, MN 55344<br>(612)829-5436 | The Rexroth Corporation<br>Industrial Hydraulics Division<br>2315 City Line Road<br>Bethelehem, PA 18017<br>(215)694-8300 |
| D. P. Technology Corporation<br>International Manufacturing Software Inc.<br>1150 Avenida Acaso<br>Camarillo, CA 93010<br>(805)388-6000 | Rockford Systems Inc.<br>P.O. Box 5166<br>Rockford, IL 61125-0166<br>(815)874-7891 |
| Do All Company<br>254 Laurel Avenue<br>Des Plaines, IL 60016-4321<br>(312)824-1122 | Technicomp<br>1111 Chester Avenue<br>300 Park Plaza<br>Cleveland, OH 44114<br>(216)687-1122  (800)255-4440 |
| Industrial Technology Institute<br>P. O. Box 1485<br>Ann Arbor, MI 48106<br>(313)769-4000 | Tompkins Associates, Inc.<br>2809 Millbrook Road, Suite 200<br>Raleigh, NC 27604<br>(919)876-3667 |
| Integrated Computer Systems<br>5800 Hannum Avenue<br>P.O. Box 3614<br>Culver City, CA 90231<br>(213)417-8888 | V-Tip, Inc.<br>P.O. Box 337<br>Rockford, IL 61105-0337<br>(815)968-5885 |
| Interactive Training Systems, Inc.<br>9 Oak Park Drive<br>Bedford, MA 01730<br>(617)271-0500  (800)227-1127 | Video Training Resource, Inc.<br>7500 West 78th Street<br>Minneapolis, MN 55435-2889<br>(612)944-8190  (800)828-8190 |

## 4.0 PARTS FLOW SIMULATION

An in-depth parts flow simulation study would be a potent ally to successful implementation of the FMS cell by uncovering many potential glitches and anticipating many problems. Simulation is the computerized creation of an exact analog of the FMS cell. Simulation can show the feasibility of alternative FMS cell designs, effects of different cell locations, optimal number and composition of jobs, how random equipment failures affect operations, system throughput, where bottlenecks will occur in the FMS cell, and interactions between different pieces of equipment. Simulation could lead to increased throughput, higher utilization of machines and labor, reduced capital and labor requirements, and better production scheduling.

Such a simulation study could be carried out on a personal computer: the necessary models can be built by computer-literate engineers with a modicum of training. However, it will be necessary, in this case, to develop simulation expertise in at least one person involved with the FMS cell; otherwise, it is probably not worth buying the software. Most simulation software houses provide one- or two-week training programs for their clients to get started in simulation, teaching them the concepts and the syntax. Coupled with assistance on the initial simulation from the vendor's consultant, this first simulation could be completed within a few months. If it is not possible to commit one person to developing the expertise to analyze the FMS cell using simulation or if simulation is required only once or twice, the best choice would be to retain the services of a consultant; expertise could also be acquired from such a consultant. Another suggestion would be to hire someone with simulation experience.

However it is done, simulation must be managed and managed aggressively. It can be managed through the use of a consultant in conjunction with a contact within AVSCOM DERSO/CCAD or it can be managed inside, to a certain degree, using off-the-shelf software. Either way there must be a commitment of time on the part of AVSCOM DERSO/CCAD to determine how the FMS cell is going to work, what assumptions to build in, what the objectives of the cell are, and what data to ignore and what to pay attention to. The sequence of steps to be followed in a simulation study is shown in Table 4.

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Table 4  Simulation Sequence

```
A.  Define
    1.  Defining goals
    2.  Making assumptions
    3.  Building models
    4.  Collecting data
B.  Program
    1.  Development
    2.  Verification
    3.  Validation
C.  Follow-up
    1.  Model testing
    2   Analysis of data output
    3.  Documentation of results
    4.  User training
```

A simpler, less detailed form of simulation is rough-cut modeling. Whereas simulation packages create exact manufacturing projections, rough-cut packages deliver an approximation. What rough-cut modeling lacks in precision, it makes up for in time. Once the necessary data are gathered, a rough model can be built with about a day of effort. Rough-cut modeling would allow the consideration of lots of different FMS cell scenarios quickly. Once there is a good idea of how to develop the FMS cell, then a more detailed simulation can be carried out if the resources are available.

Currently, three companies market software packages for rough-cut modeling - Network Dynamics (128 Wheeler Road, Burlington, MA 01803 (617) 270-4120), Palladian Software of Cambridge, Massachusetts, and Pritsker & Associates, Inc. (8910 Purdue Road, Suite 500, Indianapolis, IN 46268, (317) 879-1011). All companies offer high- and low-end versions of their packages. Network Dynamics has Manuplan, which runs on Digital Equipment, IBM, Prime, and Sun mainframes and workstations; and Manuplan II, which runs on the IBM Personal Computer AT. Palladian has Operations Advisor, which runs on Apollo Domain Series 4000, Symbolics 3600, and Texas Instruments Explorer workstations; and Operations Planner, which runs on IBM PC XTs and ATs.

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Pritsker & Associates has XCELL which runs on PCs. With any of these
packages, it takes less than a day to build most models and anywhere from a
few seconds to several minutes to run an analysis. None requires any
particular programming expertise. All are designed to be used by the people
who most need the results. All of these packages have links to simulation.
Palladian's has a built-in simulation module; Network Dynamics' works with a
program called SimStarter that automatically generates simulation code for use
with the Siman simulation package from System Modeling Corporation (The Park
Building, 504 Beaver Street, Sewickley, PA 15143, (412) 741-3727). They can
also do cost accounting: Palladian's function is built in; Network Dynamics'
Manuplan II uses Lotus 1-2-3 as a front end. Both companies claim their
packages are accurate to within 5 percent. Though gathering of the data is
the most time-consuming part of using any rough-cut package, it need not be as
detailed as the data needed for a simulation.

If full simulation turns out to be the most appropriate course for the
FMS cell, there is a wide array of simulation choices available. Powerful
general-purpose simulation languages that run on a variety of computer
platforms can be bought off-the-shelf. Or one of the growing number of
packages tailored for specific end-use applications can be selected. The
language can either be bought for AVSCOM DERSO/CCAD use or the services of a
consultant can be hired. Not including engineering staff time or consulting
costs, the prices for these languages and packages range from under $1000 up
to $100,000, depending on the complexity and power of the language, the size
of the application, and whether a sophisticated graphics or animation post
processor is added.

The grandfather of general-purpose languages is the General Purpose
Simulation System, or GPSS. Invented in 1961 by IBM Corporation computer
scientist Geoffrey Gordon, GPSS views the world as a series of separate events
or transactions occurring on a network. The early versions of GPSS ran in
batch mode on IBM mainframes. Today's descendant, GPSS/H, maintained by
Wolverine Software Corporation (7630 Little River Turnpike, Suite 208,
Annandale, VA 22003-2653, (703) 750-3910), runs much faster - and
interactively - on a variety of environments from IBM mainframes and Digital
Equipment Corporation minicomputers to UNIX workstations and MS-DOS personal
computers. The only change between hardware environments is the allowable
size of the problem.

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Other principal general-purpose simulation languages include SLAM from Pritsker & Associates, Inc. (8910 Purdue Road, Suite 500, Indianapolis, IN 46268, (317) 879-1011) and Siman from System Modeling Corporation (The Park Building, 504 Beaver Street, Sewickley, PA 15143, (412) 741-3727). The major distinction is that SLAM was written for mainframes, while Siman originated on personal computers. Today, both are migrating toward workstations.

In the past five years several PC-based general purpose languages have also emerged. GPSS/PC from Minuteman Software (P.O. Box 171, Stow, MA 01775-0171, (508) 897-5442) is an adaptation of GPSS for the PC environment, adding an interactive text editor/debugger along with interactive graphics to depict the problem in flow chart form. Siman has a similar capability. Other PC-based languages use simpler front ends for input. See Why from Istel Incorporated (60 Mall Road, Burlington, MA 01803, (617) 272-7333) integrates graphics, so a user can build not only the model code but the physical layout interactively. Another PC-based language, Micro Saint from Micro Analysis and Design, Inc. (9132 Thunderhead Drive, Boulder, CO 80302, (303) 442-6947), relies strictly on a menu-based approach - no code is involved.

A number of interactive tools are also available. They rely on menu- or graphics-driven interfaces featuring common terminology in place of generic simulation terms. They are simpler to use, although they may lack some of the versatility of the general-purpose languages. Such packages include the microcomputer-based Witness from Istel and the work-station-based MAP/1 from Pritsker & Associates. Hocus, another work-station-based package, was recently imported from England by P-E Inbucon (4118 Murphy's Run Court, Hampstead, MD 21074, (301) 374-5920). Another product, GPSS-based Automod from Autosimulations, Inc. (P.O. Box 307, Boutiful, UT 84010, (801) 298-1398), is optimized for material handling, although the vendor claims it is also suitable for general manufacturing.

Once the FMS cell has been simulated and built, Factor from Factrol Inc. (P.O. Box 2529, West Lafayette, IN 47906, (317) 463-3637) can use a different form of modeling to produce daily or weekly production schedules.

The past five years have seen the explosion of graphics for model-building and animation for presentation purposes. Some of the animations, such as System Modeling's Cinema, provide bit-mapped graphics as vivid as the best CAD programs. Automod from Autosimulations even charts them

in three dimensions. Animation is either built into the model or provided as an add-on model. Besides Istel's Witness and See Why, Autosimulations' Automod also has it built in. The advantage is convenience - a model can be built entirely using graphics, while the code is automatically generated. This approach also lets the user change the structure or logic of a model - not just its parameters - on the fly as bottlenecks appear on the screen. The other major animation packages - such as TESS from Pritsker & Associates, Cinema from System Modeling, GPSS/PC Animator from Minuteman, and Animate from Micro Analysis - place animation in a separate module. The advantage is versatility.

The considerations given above can guide the further addressing of parts flow simulation for the FMS cell.

# 14.0 BIBLIOGRAPHY WITH ABSTRACTS FOR NDE IN FLEXIBLE MANUFACTURING SYSTEMS

# 14.0 BIBLIOGRAPHY WITH ABSTRACTS FOR NDE IN FLEXIBLE MANUFACTURING SYSTEMS

Armbruster, K.; Martini, P.; Nehr, G., and Rembold, U., "A Real-Time Vision System for Industrial Application," *Proceedings of 2nd IFAC/IFIP Symposium*, New York, October 1979, pp. 253-263.

In this paper, a real-time vision system for industrial application is described. The prototype system consists of a photodiode camera, special hardware modules for image preprocessing and a controlling microcomputer. Circular coding of the image was used to facilitate the analysis of the binary image. During a teach-in phase, the vision system extracts shape descriptors. In a measuring phase, this stored reference data are compared with the corresponding features of separated, randomly oriented parts. After the identification of an object, its position and orientation are determined. This fast vision system was designed as an essential part for a flexible and versatile manipulating system. But it also performs inspection tasks for quality control.

Cardew, A. St. E., "Overview of Automated Inspection and Product Control in Europe," *Procedures of the 8th International Conference on Automated Inspection and Product Control*, Bedford, England, June 1987, pp. 23-25.

Automated inspection and product control is playing an increasingly important role in Europe accelerated to a great extent by the competition felt by the automotive and aerospace industries. One measure of the adoption of advanced measurement and inspection systems is provided by the demands placed on manufacturers of equipment for systems capable of being integrated into machining cells and flexible manufacturing systems (FMS). This article looks at the European scene through examples of the application of coordinate measuring machines, vision systems, and robots. A significant development is the adoption of quality management systems, machine capability studies, and statistical process control (SPC) and statistical quality control (SQC) techniques.

Chui, K. S., and Adams, D. L., "Part Selection for Flexible Manufacturing Cells," *The Southern Manufacturing Technology Conference Proceedings*, Charlotte, NC, January 1987.

Many issues are involved in selecting and preparing parts for flexible cells. Consideration should be given to set-up and changeover times, scheduling, quality control, tooling, fixturing and process documentation. Case histories will be discussed.

Dornfeld, D. A., "Monitoring of the Machining Process with Acoustic Emission Sensors," *Journal of Acoustic Emission*, Jan-Jun 1989, pp S227-S230.

Achieving untended manufacturing has been identified as one of the most challenging obstacles to the development of integrated flexible manufacturing systems. Sensors function as the basic element for collection of information on the manufacturing process, its tools, and the system in which it functions for use in quality and process control. Research over the last several years has established the effectiveness of acoustic emission (AE) based sensing methodologies for machine condition analysis and process monitoring. Acoustic emission has been proposed and evaluated for a variety of sensing tasks as well as for use as a technique for quantitative sstudies of manufacturing processes. This paper discusses some of the motivations and requirements for sensing in automated or untended machining processes as well as reviews the research on AE sensing of tool condition (wear and fracture) in machining. The background for AE generation in metal cutting and its relationship to the condition of the cutting tool for single and multiple point tools (turning and milling) is presented. Research results are summarized relating to the sensitivity of AE signals to process changes, AE signal sensitivity to tool condition for wear and fracture, AE signal processing methodologies for feature extraction including time series modeling to remove influences of machining conditions on wear tracking and AE sensor fusion using neural networks for process monitoring with several sensors.

Draper, C. S., Lab, Inc. *Flexible Manufacturing System Handbook, Vol. III, Buyers'/Users' Guide*, Cambridge, MA, February 1983, 114 p.

> This is the third volume in a five-volume series designed to serve as a more detailed guide to planners at corporate and plant levels closer to the manufacturing environment. It shows how to specify and purchase an FMS and then deals with installation and operation. Volume IV contains a sample request-for-proposal, a proposal, a glossary of FMS terms, a bibliography, and other technical material. Volume V contains user's manuals for various software packages.

Ercole, M., "The Integrated Flexible Dimensional Inspection," *Proceedings of the 7th International Conference on Automated Inspection and Product Control*, Bedford, England, March 1985, pp 241-251.

> The aim of this paper is to analyze the current state of the art, and to emphasize the most urgent problems to be solved, in order to create a global and centralized computer assisted quality assurance capable of influencing in real time the quality level generated by the manufacturing process.

Jones, B.E., "Sensors in Industrial Metrology," *Journal of Physics E: Scientific Instruments*, Woodbury, NY, September 1987, pp. 1113-1126.

> Industrial metrology is concerned with sensors to measure movement of machine tool parts and monitor tool wear and the dimensions of artefacts in machining centres, sensors for robots in flexible manufacturing systems, sensors to gauge mating parts for selective assembly or allowing for interchangeability and sensors for inspection and testing of assembled or part-assembled products. Sensors are required in all the widely differing manufacturing fields. In general the dimensional, shape and physical properties of functional parts need to be inspected. As a consequence of the competitive need of industry to be highly efficient and quality conscious, manufacturing metrology is evolving from traditional engineering metrology dominated by the skills of quality inspectors at the end of production lines, to automatic inspection methods off-line, in-cycle, and in-line, and utilising microelectronic, computer (hardware and software) and novel optical techniques. Suitable sensing techniques, sensors and transducers are essential to this developing situation. The paper reviews the subject and emphasizes significant advances, from the use of resonant sensor systems, edge-sensing profilers and methods of laser scanning, to acoustic emission techniques, imaging systems and the scanning tunnelling microscope. A bibliography, a listing of recent relevant conference proceedings, and an extensive list of references are provided.

Kruger, R. P. and Thompson, W. B., "A Technical and Economic Assessment of Computer Vision for Industrial Inspection and Robotic Assembly," *Proceedings of IEEE*, Piscataway, NJ, December 1981, pp. 1524-1538.

> The use of computer vision to detect, measure, and perhaps guide the assembly of man-made components is potentially a very significant research and development area. The efficacy of these techniques for any given application depends on both technical and economic considerations. This paper will explore both these considerations using appropriate generic examples. It is our goal to first present a concise discussion of the present state of many technical and economic factors and then extrapolate these factors into the future for the purpose of guiding further investigations.

Marczinski, H. J. and Banning, J., "Flexible Automated Production in Closed Die Forging and Ring Rolling," *Proceedings of the 1st International Machine Tool Conference*, Birmingham, England, June 1984.

> Wide range of different forgings in small run jobs demand versatility and flexibility of competitive production plants including short change overtimes with frequently varying programs. This has to be accomplished in a different way with regard to mechanization and automation as compared to high volume production. This should include online heat treatment and quality control. Saving of energy, reduction of waste material are two other major objections of economy in general. Plant layouts are presented, showing versatile closed die forging lines which can produce one forging in a number of different steps or can be split up into several independent units producing different

forgings simultaneously. The possibilities in forging annular parts are highlighted by closed die forging, by use of a preforming ring mill and by ring rolling. Rolling of crown wheels, roller bearing races, flanges, and jet engine rings in diameters from 150 to 1500 mm and grades ranging from carbon steels to super alloys are discussed.

Mullins, P., "How Automated Inspection is Getting It Right the First Time," *Production*, March 1986, pp 30-32.

No abstract available.

Pugh, A., "Robot Vision and Sensory Controls," *Proceedings of the 4th International Conference*, London, England, October 1984.

These proceedings consist of 48 papers with the general theme of educating and introducing to industry advanced manufacturing methods based on vision and other sensing techniques. The papers dealing with NDE are quality control with a robot-guided electro-optical sensor. Development of an expert vision system for automatic industrial inspection; and Heuristic method of classification and automatic inspection of parts; the recognition system of anima; and inspecting complex parts and assemblies.

Ranky, P. G., "Real-Time Quality Control Feedback Loops in CIM (Computer Integreated Manufacturing) Environment," *Proceedings of the 8th InternationalConference of Automated Inspection and Product Control*, Chicago, June 1987, pp 23-25.

The concept of Computer Integrated Manufacturing (CIM) provides the necessary resources, the feedbackdata as well as the material requirements for a computer controlled fabrication environment in which the order processing, the design, the manufacturing process planning, the actual fabrication process, assembly,test, etc., packaging and shipping activities include different quality control and quality assurance methods as one of their integrated functions (rather than as a separate station or function only) in order to meet the required reliability and quality specifications. There is, of course, nothing new in this concept, since the old fashioned family business could and still can solve this problem more or less without any trouble, on a small scale, though. Today, the trick is to provide high product, equipment, service, etc. Quality at a very low additional cost or no additional cost at all, preferably imbedded into every aspect and level of the operation (when and where things happen), even in industries which employ several hundred thousand people, which are geographically wide spread and culturally different. In short, this paper intends to highlight some of the above discussed problems and provide some generic solutions with practical examples for creating real-time feedback control loops in order to assure high product and equipment quality in CIM.

Shapiro, S., "Getting the Most out of Today's Technology," *Computer Design*, July 1986, pp 76+.

No abstract available.

Souder, C.W., "Applications of Visual Task Automation in Aerospace Manufacturing," *Proceedings of Society of Photo-Optical Instrumentation Engineers*, Los Angeles, February 1980, pp. 44-53.

A major emphasis is being placed on visual task automation in the aerospace industry. Computers and real-time hardware are performing image processing functions such as radiograph enhancement, non-contact mensuration, and robotic vision. This paper discusses some of these visual task problems which exist in the manufacturing of aircraft and the types of image processing which can and are being applied to these problems.

**APPENDIX A – COVER SHEETS (ONLY) AND WORKSHEETS FROM PAMPHLET SERIES 750-2**

# APPENDIX A – COVER SHEETS (ONLY) AND WORKSHEETS FROM PAMPHLET SERIES 750-2

AVSCOM PAMPHLET

AVSCOM 750-2(1)

## MAINTENANCE OF SUPPLIES AND EQUIPMENT

## AIRCRAFT ANALYTICAL CORROSION EVALUATION REQUIREMENTS

## FOR
## ARMY MODEL
## UH-1 H/V
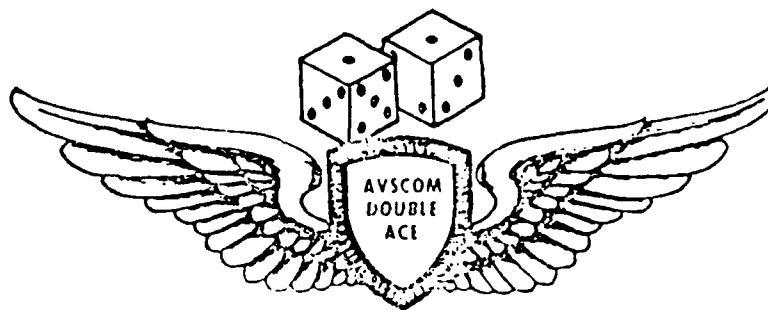


## US ARMY AVIATION SYSTEMS COMMAND

AVSCOM PAMPHLET                              AVSCOM 750-2(2)

# MAINTENANCE OF SUPPLIES AND EQUIPMENT

# AIRCRAFT ANALYTICAL CORROSION EVALUATION REQUIREMENTS

# FOR

# ARMY MODEL

# OH-58



# US ARMY AVIATION SYSTEMS COMMAND

# MAINTENANCE OF SUPPLIES AND EQUIPMENT

# AIRCRAFT ANALYTICAL CORROSION EVALUATION REQUIREMENTS

## FOR
## ARMY MODEL
## AH-1/TH-1



# US ARMY AVIATION SYSTEMS COMMAND

AVSCOM PAMPHLET

AVSCOM 750-2(5)

# MAINTENANCE OF SUPPLIES AND EQUIPMENT

# AIRCRAFT ANALYTICAL CORROSION EVALUATION REQUIREMENTS

# FOR

# ARMY MODEL

# CH-47
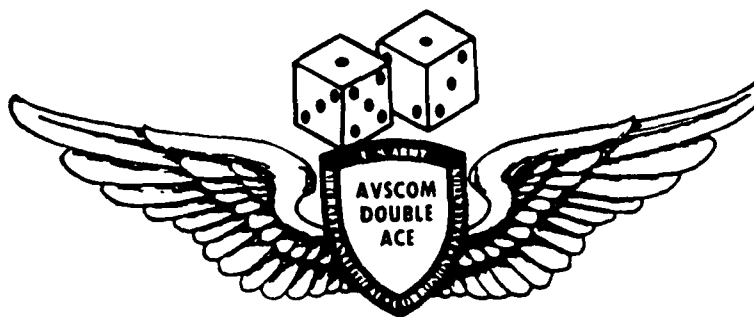
# US ARMY AVIATION SYSTEMS COMMAND

AVSCOM  PAMPHLET

AVSCOM  750-2(14)

MAINTENANCE  OF  SUPPLIES  AND  EQUIPMENT

AIRCRAFT  ANALYTICAL  CORROSION  EVALUATION  REQUIREMENTS

FOR

ARMY  MODEL

UH-60

US  ARMY  AVIATION  SYSTEMS  COMMAND

AVSCOM PAMPHLET

AVSCOM 750-2(16)

# MAINTENANCE OF SUPPLIES AND EQUIPMENT

# AIRCRAFT ANALYTICAL CORROSION EVALUATION REQUIREMENTS

# FOR

# ARMY MODEL

# AH-64



# US ARMY AVIATION SYSTEMS COMMAND

| | MASTER | UNIT | LOCATION |
|---|---|---|---|
| AIRCRAFT ANALYTICAL CORROSION EVALUATION (AACE) UH-1H/V (AVSCOM Pamphlet 750-2(1) ) | | | |

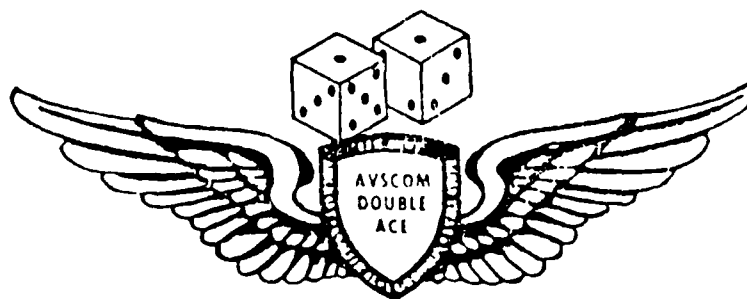| CARD COL | PROFILE | INDICATOR NOMENCLATURE | ITEM | |
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| 01 | 7 | TYPE/MODEL/SERIES | 1 | AIRCRAFT SERIAL NO. |
| 02-08 | | SERIAL NUMBER | 2 | |
| 09 | | SPECIAL MISSION | 3 | |
| 10 | | MAJOR COMMAND | 4 | |
| 11-12 | | PRESENT LOCATION OF A/C | 5 | |
| 13-16 | | JULIAN DATE OF INSPECTION | 6 | |
| 17-20 | | JULIAN DATE ENTERING PRESENT LOCATION | 7 | |
| 21-24 | | JULIAN DATE ENTERING PREVIOUS LOCATION | 8 | |
| 25 | | PREVIOUS MAJOR COMMAND | 9 | |
| 26-27 | | PREVIOUS GEOGRAPHICAL LOCATION | 10 | |
| 28-31 | | TOTAL HRS ON A/C | 11 | |
| 32 | A B C D E F R | BATTERY SHELF (NOSE COMPT) | 12 | |
| 33 | A B C D E F R | LOWER WINDSHIELD FRAME | 13 | |
| 34 | A B C D E F R | L/H OUTBD JACK PAD FITTING | 14 | |
| 35 | A B C D E F R | L/H AUXILIARY FUEL FITTING | 14 | |
| 36 | A B C D E F R | FWD TUNNEL SUPPORT ANGLES | 15 | |
| 37 | A B C D E F R | L/H FWD BOTTOM FUEL CELL PANEL F.S. 102-155 | 16 | |
| 38 | A B C D E F R | AFT TUNNEL SUPPORT ANGLES | 15 | |
| 39 | A B C D E F R | L/H & R/H EXTERNAL STORES FITTINGS | 17 | |
| 40 | A B C D E F R | CENTER INTERIOR LOWER SKIN F.S. 102-123 | 18 | |
| 41 | A B C D E F R | L/H PYLON PANEL FWD & AFT F.S. 155-166 (B.L.14) | 19 | |
| 42 | A B C D E F R | MAIN LIFT BEAM ASSY | 21 | |
| 43 | A B C D E F R | L/H UPPER AFT CABIN PANEL F.S. 166-L/H | 19 | |
| 44 | A B C D E F R | L/H LOWER AFT CABIN PANEL F.S. 166 | 19 | |
| 45 | A B C D E F R | L/H UPPER CAP F.S. 155-166 (B.L. 14) | 20 | |
| 46 | A B C D E F R | L/H UPPER CAP F.S. 168-211 (B.L. 14) | 20 | |
| 47 | A B C D E F R | L/H OUTBD HORIZONTAL UPPER ANGLE F.S. 178 | 22 | ACE FY |
| 48 | A B C D E F R | L/H OUTBD PANEL F.S. 211 | 19 | |
| 49 | A B C D E F R | BOTTOM AFT CENTER SKIN F.S. 211-243 | 18 | |
| 50 | A B C D E F R | L/H SERVICE WORK DECK | 23 | |
| 51 | A B C D E F R | FWD CENTER ENGINE DECK F.S. 155-211 | 24 | |
| 52 | A B C D E F R | SPLIT DECK F.S. 211-243 | 25 | |
| 53 | A B C D E F R | TAILBOOM ATTACH FITTINGS 4 EA F.S. 243 | 26 | |
| 54 | A B C D E F R | ELECTRICAL CONNECTORS (ALL AREAS) | 27 | |
| 55 | A B C D E F R | R/H OUTBD JACK PAD FITTING | 14 | |
| 56 | A B C D E F R | R/H AUXILIARY FUEL FITTING | 14 | |
| 57 | A B C D E F R | R/H FWD BOTTOM FUEL CELL PANEL F.S. 102-155 | 16 | |
| 58 | A B C D E F R | FWD ROOF INNER SKIN (ANTENNA) | 28 | |
| 59 | A B C D E F R | R/H PYLON PANEL FWD AND AFT | 19 | |
| 60 | A B C D E F R | R/H UPPER AFT CABIN PANEL F.S. 166 | 19 | |
| 61 | A B C D E F R | R/H LOWER AFT CABIN PANEL F.S. 166 | 19 | |
| 62 | A B C D E F R | R/H UPPER CAP F.S. 155-166 (B.L. 14) | 20 | |
| 63 | A B C D E F R | R/H UPPER CAP F.S. 178-211 (B.L. 14) | 20 | |

| NAME PROFILER | RECORDS |
|---|---|

AMSAV-M Form 1231
  31 Jan 88

Edition of 1 Dec 85 is obsolete

| AIRCRAFT ANALYTICAL CORROSION EVALUATION (AACE) OH-58A/C (AVSCOM PAM 750-2(2)) | MASTER | EAM | UNIT | AREA | LOCATION | AIRCRAFT SERIAL NO. |
|---|---|---|---|---|---|---|
| | | | | | | |

| CARD COL | PROFILE | INDICATOR NOMENCLATURE | ITEM | |
|---|---|---|---|---|
| 01 | 3 | TYPE/MODEL/SERIES | 1 | |
| 02-08 | | SERIAL NUMBE | 2 | |
| 09 | | SPECIAL MISSION | 3 | |
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| 11-12 | | PRESENT LOCATION OF A/C | 5 | |
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| 21-24 | | JULIAN DATE ENTERING PREVIOUS LOCATION | 8 | |
| 25 | | PREVIOUS MAJOR COMMAND | 9 | |
| 26-27 | | PREVIOUS GEOGRAPHICAL LOCATION | 10 | |
| 28-31 | | TOTAL HOURS ON A/C | 11 | |
| 32 | A B C D E F R | UPPER & LOWER WINDSHIELD FAIRING (NOSE SEC.) | 12 | |
| 33 | A B C D E F R | FWD SHELL ASSY (EXTERIOR) F.S. 36-96 | 13 | |
| 34 | A B C D E F R | AFT SHELL ASSY (EXTERIOR) F.S. 96-130 | 14 | |
| 35 | A B C D E F R | FWD & AFT CROSSTUBES ATTACH FITTINGS (4 EA) | 15 | |
| 36 | A B C D E F R | AFT SECTION BOTTOM FAIRING ASSY F.S. 130-194 | 16 | |
| 37 | A B C D E F R | COPILOT'S DOOR | 17 | |
| 38 | A B C D E F R | COPILOT'S FLOOR | 18 | |
| 39 | A B C D E F R | COPILOT'S SEAT COVER ASSY (OUTBOARD) | 19 | |
| 40 | A B C D E F R | CIRCUIT BREAKER PANEL (OVERHEAD) | 20 | |
| 41 | A B C D E F R | BULKHEAD ASSY F.S. 73 | 21 | |
| 42 | A B C D E F R | CENTER POST ASSY | 21 | |
| 43 | A B C D E F R | PASSENGER FLOOR L/H | 18 | |
| 44 | A B C D E F R | TRANSMISSION SUPPORT BRACKETS (4 EA) | 22 | |
| 45 | A B C D E F R | AVIONICS COMPARTMENT PANEL | 23 | AACE FY |
| 46 | A B C D E F R | ROOF SKIN, FWD | 24 | |
| 47 | A B C D E F R | ROOF SHELL ASSY L/H F.S. 75-130 | 25 | |
| 48 | A B C D E F R | AFT FUSELAGE UPPER SKIN L/H F.S. 130-205 | 26 | |
| 49 | A B C D E F R | AFT FUSELAGE LOWER SKIN L/H F.S. 165-205 | 26 | |
| 50 | A B C D E F R | BATTERY COMPARTMENT FLOOR | 27 | |
| 51 | A B C D E F R | AFT FUSELAGE UPPER SKIN R/H F.S. 130-205 | 26 | |
| 52 | A B C D E F R | AFT FUSELAGE LOWER SKIN R/H F.S. 130-205 | 26 | |
| 53 | A B C D E F R | FUSELAGE FRAME F.S. 143 | 28 | |
| 54 | A B C D E F R | FUSELAGE FRAME F.S. 155 | 28 | |
| 55 | A B C D E F R | TAIL ROTOR DRIVE SHAFT HANGER BRACKETS | 29 | |
| 56 | A B C D E F R | 90° GEARBOX | 32 | |
| 57 | A B C D E F R | TAIL ROTOR HUB ASSY | 29 | |
| 58 | A B C D E F R | TAILBOOM HORIZONTAL STABILIZERS L/H & R/H | 30 | |
| 59 | A B C D E F R | TAILBOOM ATTACH FITTINGS (4 EA) | 29 | |
| 60 | A B C D E F R | TAILBOOM INTERIOR SKIN 1ST BAY | 31 | |
| 61 | A B C D E F R | ENGINE | 29 | |
| 62 | A B C D E F R | ENGINE MOUNT L/H | 29 | |
| 63 | A B C D E F R | ENGINE MOUNT CENTER | 29 | |

| NAME PROFILER | RECORDS |
|---|---|
| | |

| CARD COL | PROFILE | INDICATOR NOMENCLATURE | ITEM | |
|---|---|---|---|---|
| | | AIRCRAFT ANALYTICAL CORROSION | MASTER | UNIT | LOCATION |

| AIRCRAFT ANALYTICAL CORROSION EVALUATION (AACE) AH-1/TH-1 (AVSCOM PAMPHLET 750-2(3) ) | MASTER | UNIT | LOCATION | AIRCRAFT SERIAL NO. |
|---|---|---|---|---|

| CARD COL | PROFILE | INDICATOR NOMENCLATURE | ITEM |
|---|---|---|---|
| 01 | 2 | TYPE/MODEL/SERIES | 1 |
| 02-08 | | SERIAL NUMBER | 2 |
| 09 | | SPECIAL MISSION | 3 |
| 10 | | MAJOR COMMAND | 4 |
| 11-12 | | PRESENT GEOGRAPHICAL LOCATION A/C | 5 |
| 13-16 | | JULIAN DATE OF INSPECTION | 6 |
| 17-20 | | JULIAN DATE ENTERING PRESENT LOCATION | 7 |
| 21-24 | | JULIAN DATE ENTERING PREVIOUS LOCATION | 8 |
| 25 | | PREVIOUS MAJOR COMMAND | 9 |
| 26-27 | | PREVIOUS GEOGRAPHICAL LOCATION | 10 |
| 28-31 | | TOTAL HOURS ON A/C | 11 |
| 32 | A B C D E F R | NOSE STRUCTURE | 12 |
| 33 | A B C D E F R | TURRET FLOOR | 13 |
| 34 | A B C D E F R | GUNNER'S FLOOR | 14 |
| 35 | A B C D E F R | AMMO FLOOR | 15 |
| 36 | A B C D E F R | PILOT'S FLOOR AREA | 16 |
| 37 | A B C D E F R | PILOT'S COMPARTMENT AFT BULKHEAD | 17 |
| 38 | A B C D E F R | BOTTOM SKINS FWD F.S. 93-136 | 18 |
| 39 | A B C D E F R | TUNNEL AREA FWD | 19 |
| 40 | A B C D E F R | BOTTOM SKIN CENTER F.S. 139-186 | 18 |
| 41 | A B C D E F R | TUNNEL AREA AFT | 19 |
| 42 | A B C D E F R | BOTTOM SKIN AFT ASSY F.S. 186-270 | 18 |
| 43 | A B C D E F R | HYDRAULIC COMPARTMENT | 20 |
| 44 | A B C D E F R | STUB WING L/H | 21 |
| 45 | A B C D E F R | STUB WING RACKS ASSY | 22 |
| 46 | A B C D E F R | PYLON AREA AND FWD ENGINE DECK | 23 |
| 47 | A B C D E F R | CENTER ENGINE DECK | 24 |
| 48 | A B C D E F R | AFT CENTER ENGINE DECK | 24 |
| 49 | A B C D E F R | OIL COOLER COMPARTMENT | 25 |
| 50 | A B C D E F R | FUSELAGE EXTERIOR | 26 |
| 51 | A B C D E F R | AVIONICS COMPARTMENT FLOOR ASSY | 27 |
| 52 | A B C D E F R | TAILBOOM ATTACH FITTINGS | 28 |
| 53 | A B C D E F R | TAILBOOM ATTACH BULKHEAD (WEB) | 29 |
| 54 | A B C D E F R | STUB WING R/H | 21 |
| 55 | A B C D E F R | STUB WING RACKS ASSY | 22 |
| 56 | A B C D E F R | FUSELAGE EXTERIOR F.S. 61-85 | 26 |
| 57 | A B C D E F R | TRANSMISSION COMPARTMENT | 30 |
| 58 | A B C D E F R | LIFT BEAM ASSY | 31 |
| 59 | A B C D E F R | MAIN TRANSMISSION | 32 |
| 60 | A B C D E F R | MAIN ROTOR HUB ASSY | 32 |
| 61 | A B C D E F R | SERVO FLIGHT CONTROL TUBES | 33 |
| 62 | A B C D E F R | MAST ASSY | 32 |
| 63 | A B C D E F R | SWASHPLATE, SUPPORT, AND SLEEVE ASSY | 32 |

NAME PROFILER

RECORDS

| AIRCRAFT ANALYTICAL CORROSION EVALUATION (AACE) CH-47 (AVSCOM PAMPHLET 750-2 (5)) | MASTER | UNIT | LOCATION | AIRCRAFT SERIAL NO. |
|---|---|---|---|---|
|  |  |  |  |  |

| CARD COL | PROFILE | INDICATOR NOMENCLATURE | ITEM |
|---|---|---|---|
| 01 | 1 | TYPE/MODEL/SERIES | 1 |
| 02-08 |  | SERIAL NUMBER | 2 |
| 09 |  | SPECIAL MISSION | 3 |
| 10 |  | MAJOR COMMAND | 4 |
| 11-12 |  | PRESENT GEOGRAPHICAL LOCATION OF A/C | 5 |
| 13-16 |  | JULIAN DATE OF INSPECTION | 6 |
| 17-20 |  | JULIAN DATE ENTERING PRESENT LOCATION | 7 |
| 21-24 |  | JULIAN DATE ENTERING PREVIOUS LOCATION | 8 |
| 25 |  | PREVIOUS MAJOR COMMAND | 9 |
| 26-27 |  | PREVIOUS GEOGRAPHICAL LOCATION | 10 |
| 28-31 |  | TOTAL HOURS ON A/C | 11 |
| 32 | A B C D E F R | BATTERY COMPARTMENT | 12 |
| 33 | A B C D E F R | FORWARD LANDING GEAR, L/H | 13 |
| 34 | A B C D E F R | FORWARD BOTTOM SKIN (COCKPIT) | 14 |
| 35 | A B C D E F R | CENTER BOTTOM SKIN | 14 |
| 36 | A B C D E F R | AFT BOTTOM SKIN | 14 |
| 37 | A B C D E F R | AFT LANDING GEAR, L/H | 13 |
| 38 | A B C D E F R | ENGINE MOUNT, L/H | 15 |
| 39 | A B C D E F R | ENGINE MOUNT, R/H | 15 |
| 40 | A B C D E F R | AFT LANDING GEAR, R/H | 13 |
| 41 | A B C D E F R | FORWARD LANDING GEAR, R/H | 13 |
| 42 | A B C D E F R | HEATER COMPARTMENT, STA. 95 | 16 |
| 43 | A B C D E F R | FORWARD TRANSMISSION | 17 |
| 44 | A B C D E F R | FORWARD F.S. 95, COMPANIONARY | 18 |
| 45 | A B C D E F R | FORWARD F.S. 120, COMPANIONARY | 18 |
| 46 | A B C D E F R | AVIONICS COMPARTMENT INTERIOR | 16 |
| 47 | A B C D E F R | FORMER F.S. 160 | 19 |
| 48 | A B C D E F R | FORMER F.S. 180 | 19 |
| 49 | A B C D E F R | FORMER F.S. 200 | 19 |
| 50 | A B C D E F R | FORMER F.S. 220 | 19 |
| 51 | A B C D E F R | FORMER F.S. 240 | 19 |
| 52 | A B C D E F R | FORMER F.S. 260 | 19 |
| 53 | A B C D E F R | FORMER F.S. 280 | 19 |
| 54 | A B C D E F R | FORMER F.S. 300 | 19 |
| 55 | A B C D E F R | FORMER F.S. 320 | 19 |
| 56 | A B C D E F R | FORMER F.S. 340 | 19 |
| 57 | A B C D E F R | FORMER F.S. 360 | 19 |
| 58 | A B C D E F R | FORMER F.S. 380 | 19 |
| 59 | A B C D E F R | FORMER F.S. 400 | 19 |
| 60 | A B C D E F R | FORMER F.S. 420 | 19 |
| 61 | A B C D E F R | FORMER F.S. 440 | 19 |
| 62 | A B C D E F R | FORMER F.S. 460 | 19 |
| 63 | A B C D E F R | FORMER F.S. 482 | 20 |

FY AACE

| NAME PROFILER | RECORDS |
|---|---|

AMSAV-M Form 1303
31 Jan 88

Edition of 1 Dec 85 is obsolete.

| AIRCRAFT ANALYTICAL CORROSION EVALUATION (AACE) UH-60A (AVSCOM PAM 750-2 (14) ) | MASTER | EAM | UNIT | AREA | LOCATION | |
|---|---|---|---|---|---|---|

| CARD COL | PROFILE | INDICATOR NOMENCLATURE | ITEM |
|---|---|---|---|
| 01 | 9 | TYPE/MODEL/SERIES | 1 |
| 02-08 | | SERIAL NUMBER | 2 |
| 09 | | SPECIAL MISSION | 3 |
| 10 | | MAJOR COMMAND | 4 |
| 11-12 | | PRESENT GEOGRAPHICAL LOCATION OF A/C | 5 |
| 13-16 | | JULIAN DATE OF INSEPCTION | 6 |
| 17-20 | | JULIAN DATE ENTERING PRESENT LOCATION | 7 |
| 21-24 | | JULIAN DATE ENTERING PREVIOUS LOCATION | 8 |
| 25 | | PREVIOUS MAJOR COMMAND | 9 |
| 26-27 | | PREVIOUS GEOGRAPHICAL LOCATION | 10 |
| 28-31 | | TOTAL HOURS ON A/C | 11 |
| 32 | A B C D E F R | AVIONICS SHELF, NOSE COMPARTMENT | 12 |
| 33 | A B C D E F R | COPILOT'S FLOOR | 13 |
| 34 | A B C D E F R | COCKPIT UNDERSEAT STRUCTURE L/H | 14 |
| 35 | A B C D E F R | FORWARD BOTTOM SKIN | 15 |
| 36 | A B C D E F R | CENTER BOTTOM SKIN | 15 |
| 37 | A B C D E F R | CARGO HOOK SUPPORT BEAM | 16 |
| 38 | A B C D E F R | AFT BOTTOM SKIN | 15 |
| 39 | A B C D E F R | FORWARD ROOF SKIN | 17 |
| 40 | A B C D E F R | AFT ROOF SKIN | 17 |
| 41 | A B C D E F R | SWASHPLATE, SUPPORT, SCISSORS AND SLEEVE | 18 |
| 42 | A B C D E F R | MAST | 19 |
| 43 | A B C D E F R | MAIN ROTOR HUB | 20 |
| 44 | A B C D E F R | FORWARD LANDING GEAR L/H | 21 |
| 45 | A B C D E F R | CARGO DOOR TRACK L/H | 22 |
| 46 | A B C D E F R | ENGINE L/H | 23 |
| 47 | A B C D E F R | ENGINE MOUNT L/H | 24 |
| 48 | A B C D E F R | TRANSMISSION MODULE L/H | 25 |
| 49 | A B C D E F R | UPPER TRANSITION SKIN | 26 |
| 50 | A B C D E F R | TRANSMISSION | 25 |
| 51 | A B C D E F R | TRANSMISSION MODULE L/H | 25 |
| 52 | A B C D E F R | ENGINE MOUNT R/H | 24 |
| 53 | A B C D E F R | ENGINE R/H | 23 |
| 54 | A B C D E F R | TRANSITION SKIN L/H | 26 |
| 55 | A B C D E F R | TAILCONE, EXTERNAL | 27 |
| 56 | A B C D E F R | TAIL ROTOR HANGER BRACKET | 28 |
| 57 | A B C D E F R | AFT LANDING GEAR | 21 |
| 58 | A B C D E F R | INTERMEDIATE GEARBOX | 29 |
| 59 | A B C D E F R | STABILATOR | 30 |
| 60 | A B C D E F R | TAIL PYLON SKIN | 31 |
| 61 | A B C D E F R | TAIL ROTOR GEARBOX | 29 |
| 62 | A B C D E F R | TRANSITION SKIN R/H | 26 |
| 63 | A B C D E F R | CARGO DOOR TRACK R/H | 22 |

NAME PROFILER                                    RECORDS

| CARD COL. | PROFILE | INDICATOR NOMENCLATURE | ITEM REF | |
|---|---|---|---|---|
| | | **Aircraft Analytical Corrosion Evaluation (AACE) AH-64 -AVSCOM PAM 750-2(16)** | **MASTER** | **UNIT** |
| 01 | Ø | Type/Model/Series | 1 | |
| 02-08 | | Serial Number | 2 | |
| 09 | | Special Mission | 3 | |
| 10 | | Major Command | 4 | |
| 11-12 | | Present Geographical Location of A/C | 5 | |
| 13-16 | | Julian Date of Inspection | 6 | |
| 17-20 | | Julian Date Entering Present Location | 7 | |
| 21-24 | | Julian Date Entering Previous Location | 8 | |
| 25 | | Previous Major Command | 9 | |
| 26-27 | | Previous Geographical Location | 10 | |
| 28-31 | | Total Hours on Aircraft | 11 | |
| 32 | A B C D E F R | Nose Skins F.S. 35-58 L/H | 12 | |
| 33 | A B C D E F R | Fuselage Skins Fwd F.S. 58-176 L/H | 12 | |
| 34 | A B C D E F R | Main Landing Gear and Shock Strut L/H | 14 | |
| 35 | A B C D E F R | Nose Gearbox L/H - R/H | 13 | |
| 36 | A B C D E F R | Canopy Structure L/H | 12 | |
| 37 | A B C D E F R | Wing and Pylons L/H | 12 | |
| 38 | A B C D E F R | Main Transmission | 13 | |
| 39 | A B C D E F R | Stationary Mast | 13 | |
| 40 | A B C D E F R | Post Actuator Flight Controls | 13 | |
| 41 | A B C D E F R | Rotating Mast | 13 | |
| 42 | A B C D E F R | Rotor Hub | 13 | |
| 43 | A B C D E F R | Equipment Deck, Fwd L/H | -- | |
| 44 | A B C D E F R | Frame F.S. 176 | 13 | |
| 45 | A B C D E F R | Frame F.S. 199 | 13 | |
| 46 | A B C D E F R | Frame F.S. 214 | 13 | |
| 47 | A B C D E F R | Frame F.S. 230 | 13 | |
| 48 | A B C D E F R | Ammo Bay Structure | 12 | |
| 49 | A B C D E F R | Fuselage Skins F.S. 230-280 L/H Bottom | 12 | |
| 50 | A B C D E F R | Equipment Compartment L/H | 12 | |
| 51 | A B C D E F R | Equipment Deck Aft and Center | 12 | |
| 52 | A B C D E F R | Engine Mounts L/H - R/H | 13 | |
| 53 | A B C D E F R | Antenna Installation | 12 | |
| 54 | A B C D E F R | Tailboom Fwd F.S. 383-436 L/H | 12 | |
| 55 | A B C D E F R | Tail Rotor Drive Shafts | 13 | |
| 56 | A B C D E F R | Tail Rotor Drive Shaft Couplings and Hangers | 13 | |
| 57 | A B C D E F R | Tailboom Skins Aft F.S. 436-547 R/H | 12 | |
| 58 | A B C D E F R | Tailrotor Hub and Post Actuator Flight Control | 13 | |
| 59 | A B C D E F R | Tailrotor Gearbox and Actuator Housing | 13 | |
| 60 | A B C D E F R | Vertical Stabilizer and Stabilator | 12 | |
| 61 | A B C D E F R | Intermediate Gearbox and Fan | 13 | |
| 62 | A B C D E F R | Aft Landing Gear and Shock Strut | -- | |
| 63 | A B C D E F R | Bulkhead F.S. 530 | -- | |

LOCATION

Aircraft Serial No.

PT AACE

NAME OF PROFILER

RECORDS

# APPENDIX B – COVER SHEETS FOR 2 SETS OF VISUAL AIDS PROVIDED TO DERSO

U.S. ARMY AVIATION SYSTEMS COMMAND

ACE/AACE

DEPOT ENGINEERING AND RCM SUPPORT OFFICE
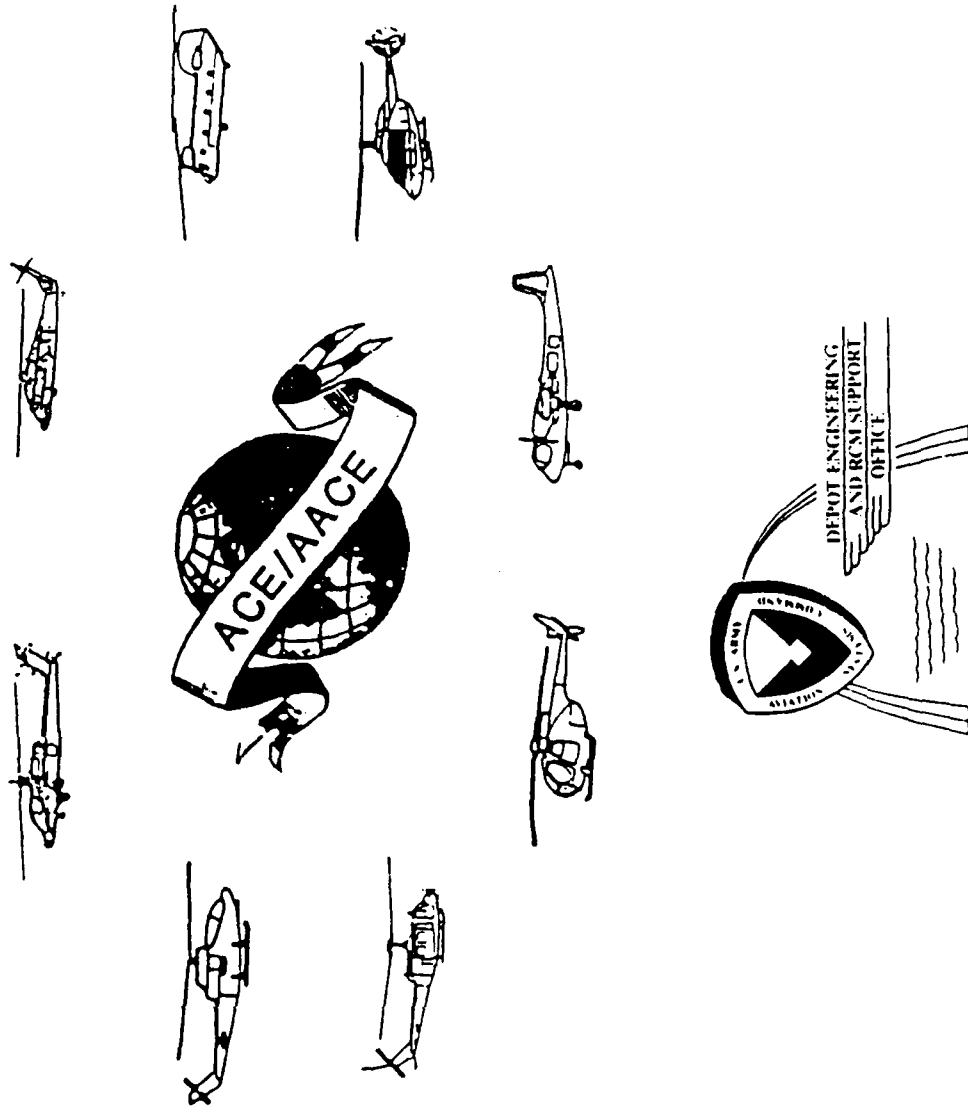
# STRUCTURING A FLEXIBLE MANUFACTURING SYSTEM

## FOR THE CORPUS CHRISTI ARMY DEPOT

U.S. ARMY AVIATION SYSTEMS COMMAND

DEPOT ENGINEERING & RCM SUPPORT OFFICE